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Investigation of integrated water level sensor solution for submersible pumps

A study of how sensors can be combined to withstand build-up materials and improve reliability in harsh environment

SARAH ABELIN

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF INDUSTRIAL ENGINEERING AND MANAGEMENT

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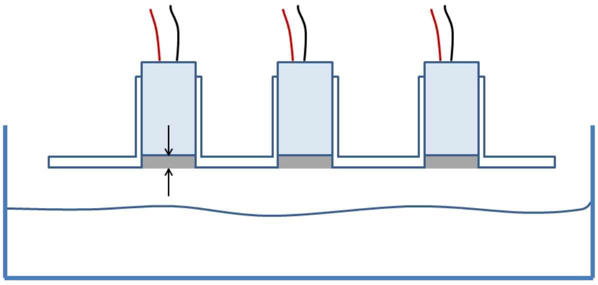

Master of Science Thesis MMK 2017:2 MDA 611
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Department of Machine Design
SE-100 44 Stockholm

KTH Industrial Engineering and Management	**Examensarbete MMK 2017:2 MDA611** **Undersökning av integrerad vattennivåsensorlösning för dränkbar pump** Sarah Abelin	
Godkänt 2017-06-01	Examinator Hans Johansson	Handledare Lei Feng
	Uppdragsgivare Xylem Inc.	Kontaktperson Jürgen Mökander

Sammanfattning

Att övervaka vattennivån i extrema miljöer för att hantera start- och stoppfunktion av dräneringspumpar har varit ett stort problem. Flera påverkande faktorer från pumpomgivningen influerar och stör sensormätningarna. Nuvarande lösningar med mekaniskt rörliga nivåvippor som är monterade utanför pumparna slits ut, trasslar in sig och står för mer än hälften av alla jourutryckningar till pumpstationerna. Eftersom pumpar ofta flyttas runt, behövs en ny sensorlösning som kan integreras i pumpen och som kontinuerligt kan övervaka vattennivån för att optimera pumpdriften och minska slitage, kostnad och energiförbrukning.

Den här masteruppsatsen presenterar en undersökning av hur olika givartekniker kan kombineras för att förbättra tillförlitligheten för övervakning av vattennivån och hantera start- och stoppfunktionen av dräneringspumpar i extrema miljöer. Fokus har legat på att identifiera lämpliga givartekniker för att mäta vattennivå och undersöka hur givare påverkas av beläggningar som byggs upp på pumpytan och täcker givarna. En support vector machine algoritm har implementerats för att kombinera givardata i syfte att öka tillförlitligheten hos givarlösningen i kontaminerat skick.

Resultaten visar att en kombination av en tryckgivare och en kapacitiv givare är den mest lämpliga kombinationen för att motstå beläggningsmaterial. För driftsförhållanden när givarna är täckta med mjuka beläggningar kunde givarna mäta vattennivån genom beläggningarna. Ingen lösning identifierades som på ett tillfredsställande sätt kunde mäta vattennivå genom stelnade, solida beläggningsmaterial.

Nyckelord: *sensor fusion, support vector machine, nivågivare, dräneringspumpar, vattennivåmätning, beläggningar, extrema miljöer*

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	Commissioner Xylem Inc.	Contact person Jürgen Mökander

Abstract

Monitoring water level in harsh environment in order to handle the start and stop function of drainage pumps has been a major issue. Several environmental factors are present, which affect and disturb sensor measurements. Current solutions with mechanical float switches, mounted outside of pumps, wear out, get entangled and account for more than half of all the emergency call outs to pumping stations. Since pumps are frequently moved around, a new sensor solution is needed which can be integrated within the pump house and is able to continuously monitor water level to optimize the operation of the pump and to decrease wear, cost and energy consumption.

This thesis presents an investigation how different sensor techniques can be combined to improve reliability for monitoring water level and handle the start and stop function of drainage pumps in harsh environment. The main focus has been to identify suitable water level sensing techniques and to investigate how sensors are affected by build-up materials building up on the pump surface and covering the sensor probes. A support vector machine algorithm is implemented to fuse sensor data in order to increase reliability of the sensor solution in contaminated condition.

Results show that a combination of a pressure sensor and a capacitive sensor is the most suitable combination for withstanding build-up materials. For operating conditions when sensors are covered with soft or viscous build-ups, sensors were able to monitor water level through the build-up materials. No solution was found that could satisfactorily monitor water level through solidified build-up materials.

Keywords: sensor fusion, support vector machine, level sensors, drainage pumps, water level measurement, build-ups, harsh environment

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With my warmest regards,

Sarah Abelin

Stockholm, Sweden, 13th March, 2017

Nomenclature

α_i	Lagrangian multiplier
c	Box constraint factor
C	Capacitance
ϵ	Electric permittivity (dielectric constant)
ε_i	Support Vector Machine slack variable
h	Deformation of elastic diaphragm
I	Current
L_p	Primitive Lagrangian Function
P	Pressure
ρ	Resistivity of conductor
R	Resistance
S	Pressure sensor sensitivity
T	Build-up thickness
U	Voltage
w	Hyperplane normal
x_i	Sensor observation
y_i	Corresponding true observation value

Table of Contents

1 Introduction

This chapter will describe the background of the thesis project. It will introduce the problem and the purpose of the thesis and present the limitations and the methodology for the conduced work.

1.1 Background

The thesis is conducted at Xylem Inc. in Sundbyberg, Stockholm, Sweden. Xylem is a global company working with water technology. A fundamental part is to develop new technologies that can improve the way of using, storing and reusing water. Xylems solutions are implemented in homes, at work, in factories and in the agriculture.

The main products developed by the company are a variety of pumps. As technology in society around us develops further a need for more intelligent solutions is seen by the company. New control systems are implemented in the pumps to improve control functionality of the operation and to optimize their operation regarding energy consumption, wear and cost. This also entails a need for more intelligent sensors feeding the control system with information.

This thesis will deal with sensor solutions for drainage pumps. The main purpose of the pumps is to keep an area dry or to keep water level below a certain point. This is managed by starting and stopping the pumps at different water levels. The level sensors currently managing the start and stop function of the pumps are mechanical variable level switches. These types of sensors wear out and get entangled and account for more than half of all the emergency call outs to the pumping stations. Some pumps are currently run without any level sensors. These are instead using snoring detection or in some cases are just pumping at all time, resulting in a lot of unnecessary dry pumping.

Keeping certain areas dry is crucial, meaning the pumps have to work properly at all time. As sensors have been a big issue and false alarms have led to many unnecessary call outs one has reasoned that it is preferred to keep the pumps running at all time. Starting and stopping the pump with the help of sensors always comes with a risk of missing a pump start, which could lead to fatal and extremely expensive consequences. However the implementation of proper sensors can also highly improve the performance of the pumps. If the operation of a pump can be optimized it will lead to a decrease in wear of the pump, in energy consumption as well as in costs. Therefore a new reliable sensor solution is needed to improve the operation and runtime of drainage pump.

1.2 Problem description

The sensors are located in harsh environment in mines with dirt, mud, moisture and a wide range of temperatures. This means several environmental factors are present which might affect the performance of a sensor. Since controlling the start and stop function of the drainage pumps is crucial the sensors need to be able to withstand these affecting factors or be able to indicate when they are malfunctioning.

Pumps operating without sensors run dry and wear out and consume unnecessary energy. This is not a sustainable option in the long run. Current sensors however do not fulfil the criteria for reliability. Today there is no single sensor that handles the start and stop function sufficiently. Further the current solution is complicated to install since it is mechanically mounted on a pre-set height beside the pump. Since pumps are being moved around a lot the new sensor solution should be integrated within the pump.

To improve the operation of the pump, water level needs to be monitored continuously. The float switches used today only indicate when water has reached a certain level but cannot give information on any other level apart from the pre-set height it has been installed at. Pressure sensors are used in some cases but have also been proven to be perturbed by ambient factors and are an expensive solution.

Apart from the environmental factors the human handling of the pumps additionally affects the requirement of the sensors robustness. Pumps are not handled with care, are often tossed around and transported on bumpy trucks. Therefore robust hardware is required combined with intelligent algorithms to handle the task.

The drainage pumps for which Xylem want to find a new liquid level sensor solution has to be able to operate in a variety of conditions:

- Position independently
- Clean and contaminated
- Temperature independently
- Withstand mechanical stress, hits and vibration
- Operate with different pumped medium

1.3 Purpose

The purpose of the thesis is to investigate how different sensor techniques can be combined to achieve sufficient result for monitoring water level and handle the start and stop function of the pumps in the given conditions from the problem description. To fulfil the purpose the following research question is formulated.

RQ: Which combination of sensor techniques is most suitable to manage start / stop function for drainage pumps?

To answer the research question the following sub research questions are formulated.

- Which environmental factors affect the sensors the most?

- How are the different sensor techniques affected by the environmental factors?
- Which sensors are most suitable for water level monitoring?
- What fusion methods can be used for combining sensors?

1.4 Delimitations

The following delimitations are set for the thesis:

- Since mechanically moving parts often have been fragile and led to early wear out only sensors with no mechanically moving parts will be investigated.
- Sensors to be investigated are sensors that can be integrated within the pump or in the pump housing i.e. sensors cannot be placed on top or side of a sump tank.
- Tests will be performed in lab environment. No field tests will be conducted.
- Tests will be performed in a test rig, not on an actual pump.
- Sensors will be tested for the influencing factors believed to affect the most, not all influencing factors.
- A cost effective solution is a wish from the company but has not been a decisive factor when investigating different technologies.

A final prototype that communicates with the actual pump drive will not be designed. The thesis is of an investigative nature and includes investigating, testing and evaluating which techniques should be used and how they could be combined to get a proper result, i.e. a proposition and base for future product development.

1.5 Research methodology

A proper research methodology needs to be chosen in order to answer the research question in a scientific way. The overall process of the thesis is described in Figure 1. The initial problem description of the thesis results in preliminary research questions and a frame of reference. The frame of reference will further specify the research focus and specify sub research questions to fulfil the purpose of the thesis. The research question entails an underlying overall hypothesis, that there is an advantage of combining several sensor techniques compared to using a single sensor.

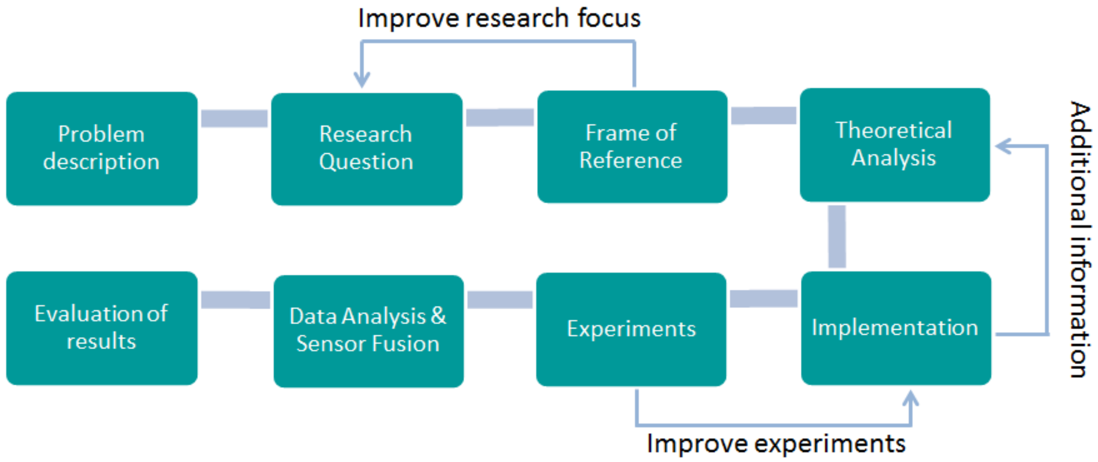


Figure 1: Thesis methodology overview.

The frame of reference includes investigation of the operating environment of the sensors, state of the art in the field of measuring water level, investigating what sensor solutions Xylem has tested so far and investigation of methods for how sensors can be combined. The study of level sensors is conducted within the area of pumps in general and drainage pumps in specific but also within other industries such as automotive industry or home appliance. The methodology for retrieving information is mainly documentary analysis of scientific articles, conference proceedings, books and reports. Further qualitative semi structured interviews are held with a reference group of four people with expertise in the area of electronics, sensors and pumping environment. An alternative for investigating operation environment could be an observational approach including field studies. This method was dismissed due to time limitations.

Information retrieved from the frame of reference results in a qualitative theoretical analysis deciding which sensor techniques are the most promising to proceed with for further testing. Further it results in determination of which affecting parameter is assumed to influence sensors the most in order to test chosen sensors in relation to this parameter. The theoretical analysis defines a sub-hypothesis of how the chosen sensors are believed to be influenced by the affecting parameter. The tested sensors can be either existing products on the market or sensors developed for Xylems special use in combination with own prototypes or adjustments of sensors for this given purpose.

The implementation phase defines the design of the experiments. An experimental research design means to recreate a situation of a phenomenon and study what happens when the situation is manipulated [1]. A test environment will be set up in a lab including hardware, software and mechanical parts in order to resemble the real operating environment where the affecting parameter can be manipulated in a measurable and repeatable way. During experiments data is collected in a quantitative manner. The experimental phase can be seen as a deductive approach where theory leads to a hypothesis that is tested and accepted or dismissed [2].

The results of the experiments will be the base of the following data analysis phase. Collected data will be fused to investigate how different combinations of sensors perform. This will deductively answer the initially underlying hypothesis of the advantage of combining sensors. However it can also be seen as an inductive approach which means moving from specific observations to wider generalizations [2]. Observations lead to detected patterns through the data analysis resulting in a tentative hypothesis of sensor combinations. The combinations are explored and result in a conclusion with a theory answering the initial research question; which combination of sensors is most suitable to manage start / stop function of drainage pumps.

1.5.1 Ethical aspect

To perform an investigation on and testing of sensor solutions is not an ethical issue as such. However one can discuss on how the solution will be implemented and used in the future. The sensors will be used for controlling the start and stop function of a pump in a harsh environment. The consequence of pump failure can result in fatal flooding resulting in high costs but also with risk for humans getting injured. Therefore the reliability of the solution must be tested and validated thoroughly. Within this thesis tests will be performed within a lab. Therefore an accurate test environment must be set up that resembles a real life scenario as good as possible. Monitored field tests should also be performed before releasing a final solution/product. However the human factor should also be taken into account and it can be discussed within a variety of areas, who solves the problem the best, a human or a machine, in this case a sensor solution with appurtenant logic, and who is most likely to make mistakes. Finally one can also take into consideration how right or wrong it is to keep a pump running continuously, even in dry state when just pumping air, and waste energy and money when there is an alternative more sustainable way of operating the pump. The ethical guidelines of The Royal Institute of Technology [3] are followed.

2 Theoretical Framework

This chapter will describe drainage pumps, the operation environment and present different sensor techniques possibly to use for this application. Further sensor fusion is investigated including support vector machine algorithms for fusing data.

2.1 Drainage pumps

The sensor solution for water level measurement is to be implemented and integrated in submersible drainage pumps. Drainage pumps are used for water drainage in harsh environments such as mines, building sites, tunnel construction and industrial plants. The pumps are durable and hardwearing and maintain performance for a long time. The sensor solution is to be implemented mainly in the smaller series of drainage pumps, weighing from 19-140kg and with a height of 570-955mm. The pumps have rated power from 0.85kW to 18kW [4]. Figure 2 shows a picture of a drainage pump located in a mine.

Figure 2: Drainage pump in mine.

The smaller drainage pumps are moved around quite often and can be moved by hand [5]. When the pumps are not operating they are stored in a utility room in the mine often without consideration about cables getting entangled. The user mainly gets in contact with the pump when it is placed out or picked up. However the user is often closer to the operation of the smaller pumps compared to the larger ones that often operate on their own over longer time. A pump operating sequence can be anything from a couple of minutes to several months. The pumps are transported to and from the sites on trucks or in tractor buckets. In general pumps are not handled with care and are often thrown down in the sump where they are to operate. The malfunction of a pump is mostly discovered randomly by miners passing the pump. When in need of service, a service technician will investigate the pump while sitting in a tractor bucket. Some maintenance work can be done from the bucket but in most cases the pump will be sent up above ground for further service [6].

2.2 Operating environment

In mines the smaller drainage pumps are primarily used for face and stage dewatering. When the front of a drift is moving forward ground and production water needs to be drained as the mining continues. This operation is quite demanding since the water has high content of solids and the water levels are low. It involves pumping both when the pumps are completely submerged but also when the pumps are only partially immersed in water. The water is pumped further back in the mine were a permanently installed pump will pump the water to the next mine level [7].

It is difficult to describe a standard operating case of a drainage pump since every situation is different but possible applications are described below. One application is draining water along a mine tunnel. The pump is standing on the ground and pumping small amounts of water. Another common application is draining water from an excavated slope constructed by the miners. These are typically 10m*10m with a water level of 2m at the deepest point. Most dirt will accumulate at the bottom of the slope and the pump is hung up to avoid pumping dirt at the bottom. A drainage pump hung up in a chain cable is shown in Figure 3 a) The pump can also be fastened within grills as seen in Figure 3 b) Another solution is to place the pump within a tank as seen in Figure 3 c), with dimensions of typically 3m*1.5m and a height of 2m.

Figure 3: a) Pump fastened in chain cable, b) Pump fastened in grill, c) Pump placed inside tank.

When moving forward in a mine, holes are drilled in the wall and filled with explosives. Holes close to the ground will be filled up with ground water and need to be drained since low water level is desirable before the explosion can be executed. During this type of drainage the pump user is generally in place.

To some extent the smaller drainage pumps are also used for open-pit drainage where surface water and ground water has to be removed from the pit to maintain production [7]. Several smaller pumps can be used to lead the water to a collecting pit [5].

The water level where the drainage pumps operate is in general quite low but can reach up to 10m. The pumps operate in anything from tight spaces to larger open pits and the speed at which water level increases or decreases in different situations varies a lot.

2.2.1 Affecting parameters

The environment within mines is moist, dirty and dark. Air humidity can be up to 90%. The ground is often muddy and cement dust from hedging the walls will build up in the mines [6]. The water is dirty and filled with gravel and particles of varying sizes. In general about 10-15 weight percent of the water is made up of dirt. Grease or fat is often floating on the water surface. All these factors lead to build-ups on the pumps and their components. Mud and drill cuttings of fine powder can create a hard concrete-like surface on the sides of the pumps. Limestone is a common problem and in some applications pumps are completely clogged with limestone after two months. Fat and foam floating on the water surface build up on the pump side when level is falling and rising. Moisture as well as water surface tension is a problem since it binds solid materials on the side of the pumps and therefore increases and speeds up the building up of materials. Rust can also affect the sensors. Depending on the mine type and different minerals present, the pH-value can vary from 3-11. Corrosion of metal occurs and could affect sensor probes.

Temperature in general is rather low, a couple of degrees Celcius but can vary widely. Several factors need to be taken into account, surrounding air temperature during operation and storage, water temperature as well as temperatures within the pump. The pumps are designed to handle water temperatures of 40°C but can operate with water up to 70°C [4]. Storage temperature of the pumps can range from -30C to +80C. Relatively high temperatures can be created by heat transmission from pump motor and shaft bearings. Air temperature inside the pump can be -10C to +100C. In drainage pumps temperature can exceed 100C during dry running.[1]

Other factors that may disturb sensors operating on the pump are vibration or mechanical impact or hits from dragging or throwing the pumps around. Vibrations occur during transport but also from the pump itself during operation. Pumps should withstand vibrations of 7mm/second in ideal conditions however vibrations up 50mm/second can occur.[1] Transport and careless handling of the pumps lead to hits and mechanical stress. Components need to be able to withstand a drop of 1m towards concrete floor with maintained electrical function and without visible damage. Fall tests with pumps are also conducted were pumps are pushed over in four directions where function and fastening devices must be maintained. As pumps are tossed around and handled carelessly there is a risk of the pump being tilted or even lying down when it is operating. Sensors need to be able to perform level measurement in these conditions also.

Electromagnetic disturbance is another factor influencing performance, especially when cables are unshielded. The main source for disturbing electromagnetic fields is the variable frequency drive within the pumps. The sensors should also not emit electromagnetic fields that can disturb surrounding components within the pump. Components should as far as possible be designed insensitive to electromagnetic disturbance.

Depending on the measuring technique of the sensor, closeness of metal can interfere with the measuring result. Mainly the metal within the pump can affect the sensor but surrounding metal constellations could also be a problem. With choice of placement of the sensor and design of a proper housing, interference could be avoided.

[1] Information retrieved from interviews with the reference group.

In mines the sensors need to be able to operate in complete darkness. Occasionally lamps or vehicle lights will light up which depending on the type of sensor could interfere with the measurement.[2]

Mines are located all over the world and on different altitudes, which also can affect sensor performance. Maximum operating amplitude for the pumps is 2000m and storage amplitude is set to 3000m.[2]

2.2.2 Physical properties of water

There are several different ways of detecting and measuring water level. In the case of mine pumping the main purpose is to distinguish between water and air. Therefore the differences in physical properties between water and air are of relevance. The physical properties of the materials can either be measured with a sensor or affect the operation of the sensor and therefore be used to identify one medium from another.

One parameter to measure is the dielectric constant or the relative permittivity i.e. the ratio of capacitance of a capacitor with a certain medium compared to the same capacitor in vacuum [8]. The dielectric constant for water is 80.4 and the dielectric constant for air is 1 [9]. Another parameter is the electric conductivity or resistivity of a medium, where water has the ability to conduct electricity while air works as an isolator. Thermal conductivity is another parameter that differs between water and air. Density of water is much higher than of air and can be used for water detection. One can measure the pressure in water compared to air pressure. It is also possible to investigate the optical properties such as refractive index or acoustic factors e.g. speed of sound.

2.3 Level measurement techniques

This chapter will discuss different sensor techniques that can be used for water detection and water level measurement. Since the sensor solution is to be integrated in the pump some techniques otherwise commonly used for level measurement are not suitable in this project and will not be discussed further here. These techniques are ultrasonic sensors, radar sensors and air bubbler devices. The techniques studied within this thesis are presented in the following subchapters.

2.3.1 Capacitive sensors

One of the most frequently used techniques for water level measurement is capacitive sensing due to its low cost and robustness in harsh environments as it can withstand high pressure and operating temperature. However a capacitive sensor can be influenced by temperature and might need temperature compensation to get accurate water level values [10], [11], [12].

The capacitive sensor works on the principle of water and air having different dielectric constants or permittivity ϵ. The dielectric constant is directly proportional to the

[2] Information retrieved from interviews with the reference group.

capacitance [10]. To measure the dielectric constant the capacitive sensors apply an electric field to the medium [13]. The sensor consists of two electrodes immersed in the medium, where the electrodes are two parallel conductive plates and the medium between the plates acts as a dielectric. The basic model of a capacitive sensor is

$$C = \frac{\epsilon \cdot A}{d} \quad (1)$$

where C is the capacitance, ϵ the permittivity of the medium, A the area of the electrodes and d the length of the space between the electrodes [14]. The electric field is reduced by the presence of a dielectric and the capacitance is inversely proportional to the electric field [15]. Depending on the amount of e.g. water between the electrodes the capacitance will change and the liquid level can be calculated from the measured capacitance [16]. The liquid level varies almost linearly with the capacitance. Several techniques can be used to measure the capacitance, e.g. capacitance to frequency conversion, an AC bridge network or charge measurement in capacitance to digital conversion [17].

A capacitive sensor can be used for both water detection and continuous level measurement. For continuous measurement the electrodes must be as long as the range of water level being measured. The capacitance between the electrodes will change along with increasing or decreasing water level. Another option is to have several capacitive sensors and measure the level in discrete steps.

Bande et al. [18], [19] designed a sensor of two opposite plates with eight identical copper zones on each plate creating eight parallel plate capacitors. The copper zones are shifted relative to each other as seen in Figure 4 to cover the whole range of water level measurement.

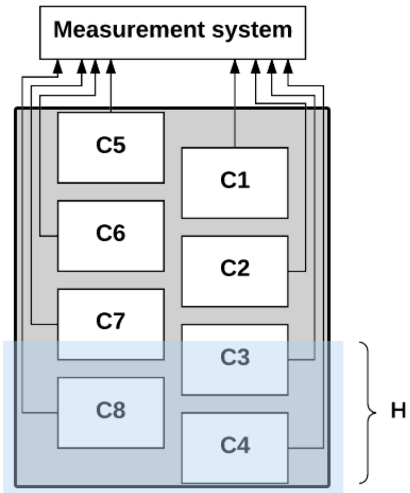
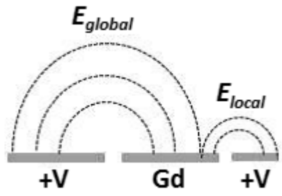


Figure 4: Sensor plate with eight shifted capacitive copper plates.

The variation of the capacitance of the partially immersed zones depends of the surfaces in contact with air and water respectively. The capacitive plates need to be immersed vertically into the measured medium to get accurate level measurement result. The sensor was proven to have a 5 mm error compared to actual liquid level.

Guirong and Shuyue [13] developed a capacitive sensor that could be used in two different modes. The first with two electrodes could be used for level measurement whereas the second mode with four electrodes could be used for measuring the gradient of a vessel containing liquid unrelated to liquid level. This could be useful when estimating water level around a water pump regardless of if it is standing up or lying down.

Since the sensors will be operating in the harsh environments of mines, build-ups on pumps as well as on sensors is a common problem. Khan et al. [10] tried to solve this by designing a sensor that utilises global and local electric fields. They divided the sensing probe into several segments to be able to detect malfunction within any segment. The global fields were used for level measurement whereas the local fields were used to detect build-ups on the segments. Figure 5 shows the electric field profiles.



[10]

Figure 5: Global and local electric fields for detecting build-ups.

Another problem is stray capacitances that can occur between electrodes and measuring circuit and deteriorate the sensor value. Narayana et al. [20] found the stray capacitance to be independent of liquid level and used it as an offset capacitance when measuring the capacitance relative to liquid level. Babu and Manohar [21] used the approach of measuring the differential capacitance between two capacitive segments which nullifies the stray capacitances. Their result was shown to be piecewise linear.

Many sensor designs use either opposite placed electrodes or sensors with a cylindrical shape with concave capacitors where the water has to enter into the formed capacitors to be measured. This can be a disadvantage since water can get stuck and result in false level measurement. Another design is proposed by B. Wang et al. [22] who designed a capacitive level sensor for a car washer tank, that could measure the capacitance through the thin wall of a plastic container. Receiver and transmitter electrodes are placed on a printed circuit board and emit an electric field as shown in Figure 6.

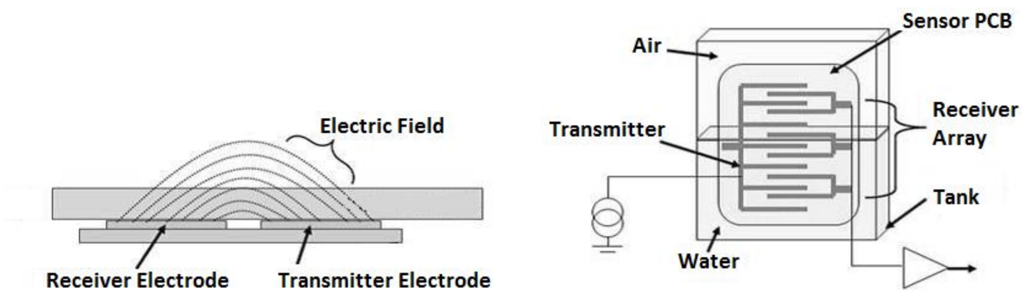


Figure 6: Design of sensor emitting an electric field through a tank wall.

This method is referred to as proximity measuring and is considered less sensitive than the contact capacitive sensing methods [23].

2.3.2 Conductive sensors

A conductive sensor is built on the principle of water being conductive compared to air which works as an isolator. The sensor is composed of two electrodes protruding into the medium measured. When water is present it completes the circuit since current can flow between the electrodes through water but not through air. Resistance can be detected between the electrodes and be compared to a reference resistance to determine the presence of water [24]. Using DC voltage within the circuit can cause electrodes to corrode over time due to electrolysis. AC voltage can be used to avoid corrosion [25]. Water as such is not necessarily a good conductor. The conductivity of water depends on its salinity or the amount of ions in the water. The electric conductivity of water also increases with increasing temperature. Conductivity is measured in μS/cm and a medium is considered conductive if its conductivity exceeds 10 μS/cm [23].

J. F. Kreutzer et al. [26] used a conductive sensor to measure the level of contents in discrete steps in a beverage cup for elderly people. The principle is shown in Figure 7 where multiple electrodes covered in gold are placed along the side of the cup and when water reaches a certain electrode it is short circuited with the electrode, thus detecting liquid at different levels.

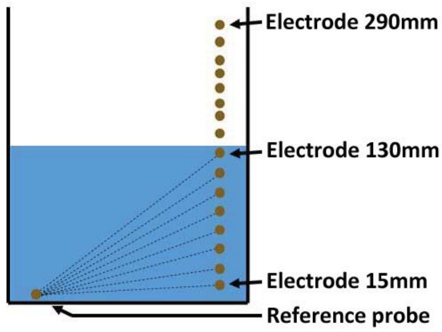


Figure 7: Principle of conductive sensor in beverage cup.

The tests were conducted with liquids of temperature between 15°C and 90°C and showed that the temperature influence on the sensor is negligible. However adhesive remnants of certain liquids such as milk influenced the electrodes and the operation of the sensor.

A similar design was used by An and An [27] for measuring water level in bad conditions in a sump tank. The electrodes were made from copper and instead of short-circuiting them to an electrode at the bottom each level segment consisted of pairs of electrodes where current could flow between those when water was present.

H.-K. Yu et al. [28] developed a thin film-tape sensor for leakage detection which could be manufactured up to 200 m long. The tape is built up of three conductive lines and one resistive line. The potential differences between the conductive and the resistance line are monitored and when water is present a closed circuit is formed between the lines and the potential changes. A pulse type voltage is applied constantly switching polarity to avoid the liquid getting polarized leading to no flowing current. The sensor was verified in temperatures from 0°C-90°C, resistant to thermal shock, humidity and a weight pressure of 1 ton. A drawback with this solution is that the sensor needs to be wiped off after water presence.

2.3.3 Optical sensors

Optical sensors are based on water and air having different refracting index. Light will change direction when passing through two different media. The sensor consists of a light source e.g. a Light Emitting Diode (LED) and a receiver, a phototransistor placed within a prism. As shown in Figure 8 most of the light will be reflected in the prism and received from the transmitter when placed in air. When the sensor is submerged, most of the light will refract into the water and the received light decreases [22].

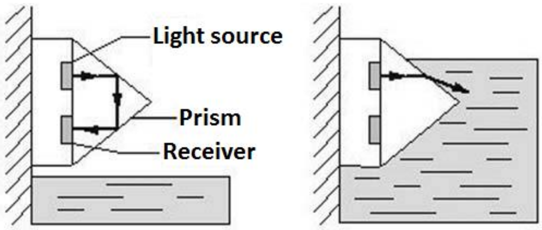


Figure 8: Light reflections for optical sensor in air and liquid.

The optical properties can also be measured by an opposed LED and phototransistor letting the light waves travel through the measured medium and be detected at the other side [29].

2.3.4 Load cells

Load cells measure water level by measuring the weight of the liquid, thus working on the principle of water and air having different density. Load cells are usually built of a strain gauge or a piezoelectric sensor [16]. A strain gauge consists of a thin foil resistor attached on an elastic material. The strain gauge is deformed by the applied force and measures the strain as change in electrical resistance. Resistance will change along with deformation of a spring element and is proportional to the applied force. The applied force must be within the elastic range of the spring element material for the relation to be linear. If the force exceeds this range it can be permanently damaged. The resistance is a function of the area and the length of the strain gauge, a conductor, and increases with increasing length and decreasing area given by

$$R = \rho \frac{l}{A} \tag{2}$$

where ρ is the resistivity of the conductor, l the length and A the area. The variations in resistance are often very small and also vary due to temperature. To enhance the measuring process load cells often use Wheatstone bridges of four strain gauges. However Wheatstone bridge strain gauges are sensitive to mechanical stress, heat variation and noise [30].

2.3.5 Pressure sensors

Pressure sensors measure the pressure in the surrounding medium to determine if it is air or water. Furthermore a pressure sensor can measure the water level continuously since the pressure in water is proportional to water depth. Water pressure depends on the density of the water and on the height of the column of the water. Pressure at a certain point is the same in all directions. If the external pressure increases the pressure at every point in the water will increase accordingly.

There are different ways of measuring pressure. One way is to measure the absolute pressure where the reference is to vacuum. In a sensor this is accomplished by sealing the reference side of the pressure transducer. Another way is to measure gage pressure, which is referenced to atmospheric pressure, where the reference side of the transducer is sealed to pressure at sea level. A third way is to measure the differential pressure between two independent pressure sources. The output is proportional to the difference in pressure between the sources. An example of this is a vented submersible pressure transducer [31]. Pressure transducers are comprised of a mechanical transduction device attached to an electrical transduction device. The mechanical transducer converts liquid energy into mechanical energy and the electrical transducer converts mechanical energy into electrical energy. Figure 9 shows a pressure sensor with a piezoelectric pressure transducer with a diaphragm as mechanical transduction element.

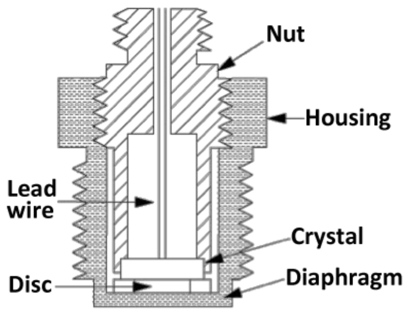


Figure 9: A piezoelectric pressure transducer using a diaphragm as force-summing device.

A piezoelectric transducer works on the principle of that some crystals and ceramic materials have the ability to generate electric charge when stressed mechanically and provides voltage proportional to the pressure. Piezoelectric transducers are often used for quickly changing pressures [31]. The principle of piezoelectricity is mostly used for pressures up to 16 bar [32]. The most commonly used transducer for pressure sensors is the strain-gage, where its electrical resistance is proportional to the length of a strained wire [31]. This type of transducer is commonly used above 17 bar [32].

A pressure sensor is affected by temperature. Within a certain range, often 0°C to +80°C, the sensors are electronically compensated for the changes in temperature. Extreme temperatures however can affect the accuracy of the sensor. Pressure sensors can also be affected by aggressive mediums containing particles of dirt or by strong vibrations or mechanical impacts. Pressure sensors are in general maintenance free but need calibration to its reference at some point [32].

The output voltage of the sensor is a function of its sensitivity

$$V = S \cdot P \tag{3}$$

where S is the sensitivity of the sensor, P the pressure and V the output voltage [33].

Park and Kim [33] used a total of seven pressure sensors for measuring the water level in a tilted environment. The seven sensors were placed around the tank as seen in Figure 10. By using the average output from the sensors the accuracy increased.

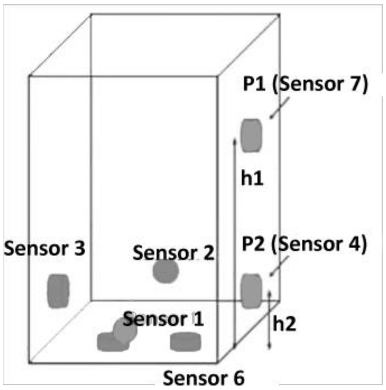


Figure 10: Placement of pressure sensors around water tank.

Apart from water level the tilted angle could be calculated by using the difference in output between the opposite placed pairs of sensors.

2.3.6 Vibration sensors

Vibration sensors typically consist of a vibrating probe where changes in vibrations are monitored. When the probe is immersed in a liquid the vibration is dampened. A piezoelectric crystal causes the probe to vibrate and another piezoelectric crystal detects the changes in vibration [34]. Vibration sensors vibrate at their natural frequency, the frequency where the system resonates. Natural frequency is dependant of the mass as well as the stiffness of the beam or the probe acting as a spring. A higher mass and a softer spring decrease the natural frequency [35]. Figure 11 shows the difference in natural frequency for some different shapes.

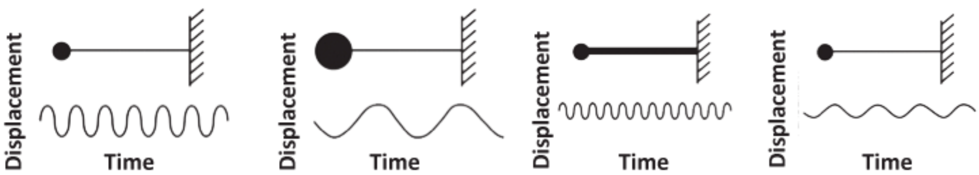


Figure 11: Differences in mass and stiffness affect the natural frequency.

When the system is damped mechanical energy from the system is dissipated and the vibrations attenuate, which is what happens when a vibrating sensor is submerged in water. The main characteristics of resonance shape due to losses in stored energy are its location i.e. the resonance frequency and the size i.e. its bandwidth.

A typical vibrating sensor is a tuning fork comprising two vibrating fork tines. Some tuning fork sensors have the ability to automatically adjust to increasing material build-ups on the probe and will give an alarm if the build-ups become too significant [36]. This makes them suitable for dirty liquids in harsh environments.

Xylem started testing a vibration sensor for detecting leakage within a pump. The sensor consisted of a piezoelectric membrane emitting a high frequency sound. When the sensor was covered by water the dampening could be detected. The sensor was tested in room temperature and in hot water at 80°C. The sensor indicated leakage after about 15 seconds of submersion and stopped indicating leakage after approximately 4 seconds in air. Since the tested sensor was totally integrated the raw signal of the sensor could not be read. The legs of the vibrating membrane were found to be quite fragile. Another problem was water getting stuck between the casing and the vibrating membrane, due to water surface tension, increasing the risk of false alarm.

2.3.7 Temperature and calorimetric sensors

A simple temperature sensor can be used to determine if water is present as long as water and air have different temperatures. If the water is significantly colder than air a sudden drop in temperature can indicate presence of water. However this technique can be somewhat limiting for certain applications. A different way would be to use a calorimetric sensor principle. A calorimetric sensor uses two thermal sensor probes where one is heated compared to the reference probe. Since water and air have different thermal conductivity there will be a difference in temperature when in air but when submerged into water the heated sensor will be cooled down by the water [37]. Monitoring the difference in temperature it can be determined if water is present or not. This can be accomplished by connecting the probes to a Wheatstone bridge creating an unbalanced circuit. When the sensor comes in contact with water the almost equal temperatures will balance the circuit [22].

2.3.8 Optical fiber sensors

Optical fiber sensors have the advantage of being of small size, light weight, having electrical isolation and being immune to electromagnetic interference [38], [39], [40], [41]. Optical fiber sensors can be used for several applications like measuring temperature, pressure or humidity [38]. The principle of optical fiber sensors is mainly based on the total internal light reflections in an optic fiber and differences of refractive index of different media and changes in wavelength shift. Power attenuation occurs when an optic fiber is submerged in water [23]. There are several types of fiber optic sensors. Micro-bend level sensors have good measurement precision but are quite difficult to install due to its deformation tooth. Macro-bend liquid level sensors measure loss in leguminous flux. They have simple structure and are not affected by temperature but the actual fiber is very fragile. Fiber grating sensors have high measurement precision but are highly influenced by temperature and the equipment is expensive [42]. Lui et al. [40] likewise state that many current applications of optical fiber sensors have the disadvantages of complex structure, expensive demodulation systems and low liquid level sensitivity. Further the influence of temperature is a common problem for optic fiber sensors since changes in temperature affects both the refractive index of liquids and also the fiber material, causing thermal expansion or contraction, which changes the aperture in the fiber [41].

Sheng et al. [38] developed a fiber-optic sensor that transforms pressure from water into axial strain which causes the Bragg wavelength to shift. The applied strain causes variations in refractive index and grating period. A polymer is pressurized in radial direction which corresponds to an axial force acting on a round plate causing axial strain on the fiber bragg grating as seen in Figure 12.

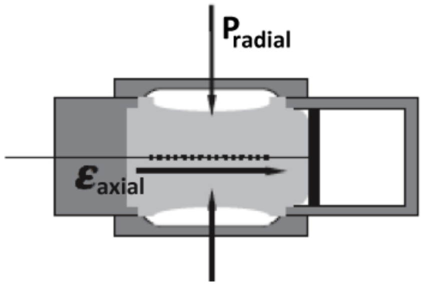


Figure 12: Polymer plate pressurized in radial direction causing fiber bragg grating to be legnthend in axial direction.

The sensor was proven to have good linearity between water level and wavelength shift with a resolution of $1.526*10^{-5}$/cm. However it was quite affected by temperature. The sensors sensitivity to temperature is $7.624*10^{-6}$/°C, meaning that a temperature change of 2°C will cause the same wavelength shift as 1cm change in water level. Thus the sensor needs compensation for temperature to be able to operate in harsh environments.

Yu et al [42] developed a sensor measuring the coupling loss between optical fibers. The sensor is comprised of two fiber sections, one receiving and one transmitting, and an elastic diaphragm. The elastic diaphragm is deformed by increasing or decreasing water level and changes the angle between the two fiber sections as seen in Figure 13. Increasing angle will result in decrease of received luminous flux.

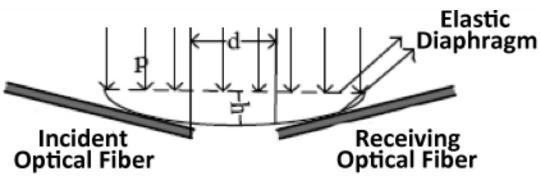


Figure 13: Deformation of elastic diaphragm changes the angle between the transmitting and receiving optical fiber.

The deformation *h* of the elastic diaphragm is proportional to water pressure *P,* which is proportional to liquid level. Knowing the relationship between the deformation *h* and the angle between the fiber sections water level can be estimated. To make sure the photoelectric detector only measures the light of the receiving fiber and to avoid influence of stray light the section of the detector as well as the fiber end was shaded.

Rosolem et al. [43] used the macro bend fiber sensor technique as a water pressure sensor for tubes in embankment dams, measuring water levels up to 10m. In the proposed design an elastomeric membrane is deformed by increasing water pressure and thereby compresses a fiber optic ring. The fiber is bent in an order of a few centimetres and causes signal attenuation. The sensor was proven to have a resolution of 0.15m. However it was observed that the sensor showed hysteresis behaviour resulting from internal friction of the membrane dissipating as heat. A proposed solution to the hysteresis problem was to use a metallic corrugated diaphragm instead of the elastomeric membrane.

2.3.9 Surface acoustic wave sensors

Surface acoustic wave (SAW) sensors use the piezoelectric effect to transform electrical signals into acoustic waves. The sensors consist of an input transducer, an output transducer and a piezoelectric substrate. The input transducer transforms the electrical signal into a sound wave traveling across the surface of the substrate and the output transducer transforms the wave back into an electrical signal. The electrical output signal reflects any changes made to the mechanical acoustic wave [44]. Figure 14 shows a model of a surface acoustic wave sensor with an input transducer, an output transducer and a wave traveling across the piezoelectric substrate.

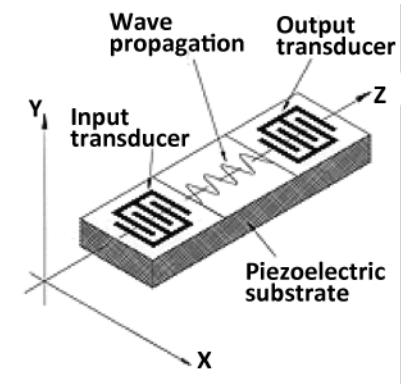


Figure 14: Surface acoustic wave sensor.

Passive SAW sensors are powered by radio waves from a radio frequency transceiver. An electromagnetic pulse is sent to the sensor. Inverted piezoelectric effect induces mechanical strain on the sensor substrate resulting in the surface acoustic wave. The physical property to be measured affects the wave when traveling across the surface. Different parameters can be monitored to detect changes to the surface acoustic wave; the delay or corresponding phase, the frequency of the electrical response or the attenuation [45].

Surface acoustic wave sensors can be used to measure several different physical parameters such as temperature, pressure and flow. For liquid detection a Love wave sensor using shear-horizontal waves was proven to be very sensitive. When liquid comes in contact with the SAW sensor the waves are attenuated excessively [46].

Xylem started testing a lab prototype for leakage indication of oil and water. The prototype is shown in Figure 15. The output transducer was driven by a signal generator with 35kHz, 10V output signal and the input transducer was connected to a oscilloscope measuring the change in amplitude and phase.

Figure 15: Prototype of surface acoustic wave sensor.

In the middle section a cup was milled out to hold the content of water and oil. The initial testing proved successful detection of both water and oil.

2.4 Sensor fusion

All sensors have different benefits and drawbacks affecting the reliability when operating on their own. Sensor fusion means combining data from different sensors with the purpose of improving output results. Elmenreich [47] presents the definition of sensor fusion by the International Society of Information Fusion as "*the combining of sensory data or data derived from sensory data such that the resulting information is in some sense better than would be possible when these sources were used individually*". Figure 16 describes how data from multiple sensors is combined to give a representation of the monitored environment before it is passed on to a control application.

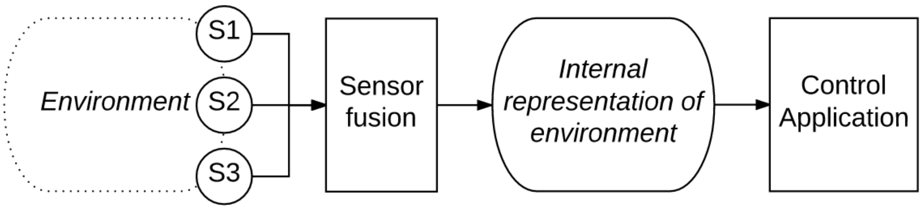


Figure 16: Sensor fusion model.

Using only a single sensor in a system comes with the following weaknesses compared to fusing data from multiple sensors. One sensor might have limited spatial coverage, being able to measure only within a specific range, whereas multiple sensors may extend this range. Sensors may also have limited temporal coverage, meaning that the highest possible sampling frequency varies between sensors. One sensor may have limited precision or resolution compared to fusing several sensors. Further, uncertainty is a limiting factor if one sensor is only able to monitor part of the environment but is unable to give information of the whole object on its own [47].

The purpose of fusing several sensors is thus to increase robustness and reliability, to extend temporal and spatial coverage, to improve resolution and reduce uncertainty and to create a system more robust against interfering factors. The optimal fused system should perform at least as good as the best individual sensor where performance correlates to the probability of taking the right decision at the right moment [47].

An implementation of sensor fusion can include both multiple sensors of the same kind and multiple sensors of different kinds [47]. Sensor fusion can be divided into three categories, competitive sensor fusion, cooperative sensor fusion, complementary sensor fusion or a combination of the three. Competitive sensor fusion means that every sensor independently measures the same property and is also referred to as redundant sensor fusion. Cooperative sensor fusion means combing data from several independent sensors to achieve information that would not be possible from a single sensor e.g. fusing 2D images from slightly different angles to retrieve a 3D view of an object. In complementary sensor fusion sensor do not depend on each other directly but can combined give a more complete view of an environment.

2.4.1 Supper Vector Machine

One way of combining data from several sensors is to use a support vector machine (SVM), a machine learning process used to classify data. The support vector machine approach was chosen for this thesis since it optimizes the decision boundary between data classes and is a robust solution even if the training data has some bias.

SVM, can be used for data that can be divided into two classes. The classification of the data is done by finding a hyperplane that separates the data points from one class from the data points in the other class. The optimal hyperplane is a plane that separates the two classes with the largest margin between the classes. The data points closest to the hyperplane are called support vectors. The distance, parallel to the hyperplane, between the support vectors makes out the margin [48]. Figure 17 illustrates a set of data points divided into two classes, with a hyperplane separating the two and the support vectors marked in circles. The data points of one class are marked with black dots and the other class is marked with white dots.

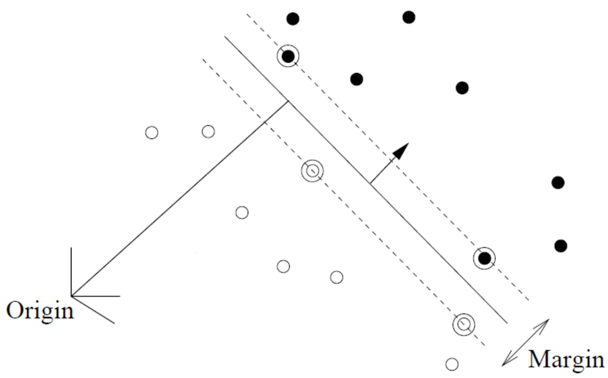


Figure 17: Hyperplane dividing two classes of data points.

Separable case

Assume data points are retrieved from l observations. Each observation is represented by a pair of vectors: a vector $\mathbf{x}_i \in R^n, i = 1, \dots, l$ representing the actual observation and a vector y_i representing the associated true value of that observation [49]. y_i can adopt two values, representing the two classes the data is to be divided into. In a situation of water detection y_i could be 1 if water is present and -1 if it is not, meaning $y_i \in \{-1,1\}$. The purpose of the SVM is to learn the mapping $\mathbf{x}_i \rightarrow y_i$ by finding a hyperplane separating the positive from the negative data. Data points $\mathbf{x}$ lying on the hyperplane will satisfy $\mathbf{w} \cdot \mathbf{x} + b = 0$. $|b|/\|\mathbf{w}\|$ is the perpendicular distance from the origin to the hyperplane, where $\mathbf{w}$ is the normal to the hyperplane. The support vector algorithm tries to find a separating hyperplane with the largest margin by assuming the data points fulfil the following constraints

$$\mathbf{x}_i \cdot \mathbf{w} + b \geq +1 \text{ for } y_i = +1 \quad (4)$$

$$\mathbf{x}_i \cdot \mathbf{w} + b \leq -1 \text{ for } y_i = -1 \quad (5)$$

which can be combined into

$$y_i(\mathbf{x}_i \cdot \mathbf{w} + b) - 1 \geq 0 \quad \forall i \quad (6)$$

Points that satisfy constraint (4) lie on a hyperplane H1: $\mathbf{x}_i \cdot \mathbf{w} + b = 1$ with perpendicular distance$|1 - b|/\|\mathbf{w}\|$ to the origin. Points that satisfy constraint (5) lie on a hyperplane H2: $\mathbf{x}_i \cdot \mathbf{w} + b = -1$ with perpendicular distance $|-1 - b|/\|\mathbf{w}\|$ to the origin. Thus the margin between the hyperplanes is $|1 - b + (-1 - b)|/\|\mathbf{w}\| = 2/\|\mathbf{w}\|$. By minimizing $\|\mathbf{w}\|^2$ we can find a pair of hyperplanes with the largest margin. The data points lying on hyperplane H1 and H2 are the support vectors [49].

To easier handle the constraints positive Lagrange multipliers $\alpha_i, i = 1, \ldots, l$ are introduced for each constraint (6). Multiplying the constraints by the Lagrange multipliers and subtracting them from the objective function form the Lagrangian

$$L_P = \frac{1}{2}\|\mathbf{w}\|^2 - \sum_{i=1}^{l} \alpha_i y_i (\mathbf{x}_\mathbf{i} \cdot \mathbf{w} + b) + \sum_{i=1}^{l} \alpha_i \quad (7)$$

To retrieve the optimal hyperplane separating the data classes, L_P needs to be minimized [49].

Non-separable case

Not all data can exclusively be divided into two classes by a hyperplane. If this is the case a SVM can use a hyperplane with a soft margin separating most but not all data points. This can be done by introducing slack variables ε_i to the constraints (4) and (5) when necessary and a cost factor c. This results in new constraints:

$$\mathbf{x}_i \cdot \mathbf{w} + b \geq +1 - \varepsilon_i \text{ for } y_i = +1 \quad (8)$$

$$\mathbf{x}_i \cdot \mathbf{w} + b \leq -1 + \varepsilon_i \text{ for } y_i = -1 \quad (9)$$

$$\varepsilon_i \geq 0 \quad \forall i \quad (10)$$

The corresponding ε_i has to exceed agreement for a misclassification to occur meaning $\sum_i \varepsilon_i$ is a bound for the number of training misclassifications. To allow cost for misclassification the objective function needs to be minimized for $\|\mathbf{w}\|^2/2 + c\sum_i \varepsilon_i$ instead of $\|\mathbf{w}\|^2/2$. This results in minimizing the Lagrangian:

$$L_P = \frac{1}{2}\|\mathbf{w}\|^2 + c\sum_i \varepsilon_i - \sum_{i=1}^{l} \alpha_i\{y_i(\mathbf{x_i}\cdot\mathbf{w} + b) - 1 + \varepsilon_i\} - \sum_{i=1}^{l} \mu_i\varepsilon_i \qquad (11)$$

where μ_i are Lagrange multipliers to impose positivity of ε_i and c ist the box constraint [49]. Figure 18 illustrates a set of data points divided into two classes in a non-separable case.

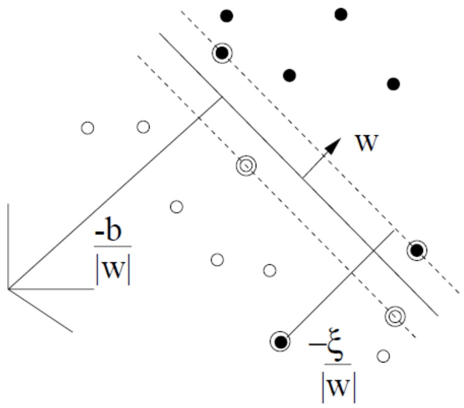


Figure 18: Hyperplane dividing data into two classes in a non-separable case.

SVM can be implemented in Matlab. The function *fitcsvm* is used to train a model by using Sequential Minimal Optimization, SMO, as a solver. The function *fitcsvm* minimizes equation (11) by a series of two point minimizations [48].

After a SVM model is trained it can be used to classify new data. This is done by determining on which side of the hyperplane new data points lie. If **x** is a new set of data points the corresponding class label is assigned by $sgn(\mathbf{w}\cdot\mathbf{x} + b)$ [48], [49].

3 Sensor Technique Analysis

This chapter describes the theoretical evaluation of the different sensor techniques in relation to the conditions the sensor solution needs to operate within. A choice of which sensors to proceed with for further testing is presented.

Looking at different sensor technique alternatives for measuring water level several factors need to be taken into account when choosing which technique to use. From the different techniques studied in the theoretical framework the few believed to be most suitable are to be chosen for further testing. Factors affecting the choice of sensors can be subdivided in different categories where the main are performance, life span, ease of implementation and cost. Appendix A contains application variables affecting the choice of sensor technology.

Within this thesis mainly the factors within performance regarding robustness and reliability have been dealt with. Since the project is conducted within a specific time limit availability of different sensor prototypes also partly has affected the choice of sensors for further testing.

The different sensor techniques studied in the theoretical framework can be divided into continuous and point level sensors. Continuous sensors measure water level continuously. Point level sensors detect water at a single point. To be able to monitor water level the point level sensors need to be placed in an array to monitor water level in discrete steps.

3.1 Use cases

To make a proper decision on which sensors to use for the purpose of monitoring water level for drainage pumps in harsh environment the use scenarios of the pumps need to be studied. The purpose of this is to identify different common and uncommon scenarios, as well as variations within these, in which the sensors need to be able to handle their task. How the pumps are used in different situations is investigated to distinguish how the sensors can be affected. From the theoretical study the following main pump scenarios have been identified:

- Draining water along a mine tunnel.
- Draining water from an excavated slope.
- Drained water from drill holes before executing an explosion.
- Open-pit drainage.

Within these areas different installations of the pumps are present, such as pumps fastened within grills or placing pumps within a tank.

Further, four main use case areas have been identified that can be applied on the different scenarios; installation, service, transport and operation. Some of which apply more for human interaction with the pump and the sensor system and some for the actual sensor system performing its task. The purpose of the human use cases is to identify what interactions from the user with the level sensor system, affects the design of the sensor. The purpose of the sensor system use cases is to identify what measurement tasks and start and stop functions the sensor system needs to handle in different pump scenarios.

Installation and *Service* are situations where a human comes in contact with the system and prepares it for different pump scenarios. *Operation* is where the sensor system performs its task and has to handle different pumping scenarios. *Transport* can affect the sensor system because of e.g. mechanical impact but does not include any interaction between human with the actual sensor system. Neither does the sensor system perform any work in this state. Thus this will rather lead to requirements on robustness.

The use cases then result in requirements the sensors need to fulfil to solve the task of monitoring water level in different situations. Figure 19 illustrates how different pump scenarios are broken down into use cases leading to requirement specification.

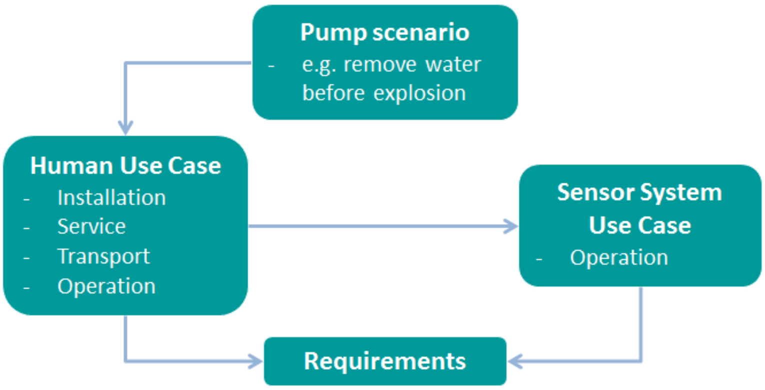


Figure 19 Model of use cases leading to requirement specification

The operation use cases were found to be the most relevant for this thesis since the main interest is to investigate how well the actual sensors manage to monitor water level. The main basic functions identified for the sensor system from the different use scenarios are:

- Keep water level between two points
- Keep water level below certain point
- Flexibly be able to change these points

Additional functions could be:

- Indicate that it is functioning on start-up and when operating
- Indicate if it is broken

Different pumping scenarios comprise different amounts of water. Water level will rise and fall at different speed. This will lead to requirements on how fast the sensor system needs to perform the level measurement. Different depths of water level affect the total range of measurement.

Environmental factors lead to requirements on withstanding moisture, build-ups and temperature. As the sensors are to be integrated within the pump there is also a risk of perturbation due to electromagnetic disturbance, vibration from pump motor as well as vicinity of metal. Looking at transport scenarios, these lead to requirements on vibration and mechanical stress. The installation scenario also leads to requirements on mechanical stress since pumps are often tossed into pounds, leading to mechanical impact which can damage the sensors. Use cases of installing and servicing the actual sensor system were considered outside of the scope of the thesis. The following sections will describe an analysis of the different sensor techniques in relation to the affecting parameters identified in the theoretical framework. A complete requirement specification is presented in Appendix B.

3.2 Placement of sensors

As the sensors are to be integrated within the pump different options of placement need to be considered. Sensors can be placed within or on the outside of the pump house anywhere from top to bottom of the pump. One possible solution could also be to place sensors inside of the stator house if they manage to measure water level through the metal wall of the pump house. Placement should be determined by how well the sensors can perform their measurement, how well they are protected from surrounding environment and how easy they are to integrate i.e. how they can be fastened and connected. Figure 20 illustrates a possible sensor placement.

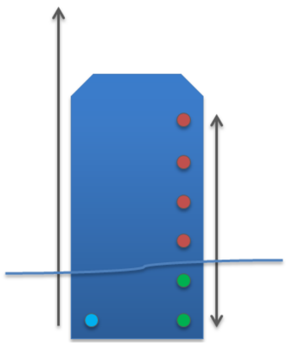


Figure 20 Possible placements of sensors on pump and measuring range

On the left side a single sensor is placed at the bottom of the pump able to perform continuous water level measurement. The water level measuring range is dependent on the chosen sensor but can in theory reach from pump bottom to water levels above the pump height. On the right side several point level sensors are placed in an array. The arrows on the side of the pump illustrate the total range of measurement over which the sensor can monitor water level. For the point level measuring sensors resolution will be determined by the distance between the sensors within the sensor array. A distance of 5cm between the sensors is considered sufficient.

3.3 Independence of orientation

As there is a risk of pumps being tilted the sensor solution needs to be able to compensate for this in order to still deliver correct level measurement data. Figure 21 and Figure 22 show some possibilities of incorrect indication when the pump is tilted or lying down. For the sensor array red colour indicates air and green colour indicates water. The other sensor measures water level continuously and is coloured in blue. The vertical blue wave shaped line represents water level.

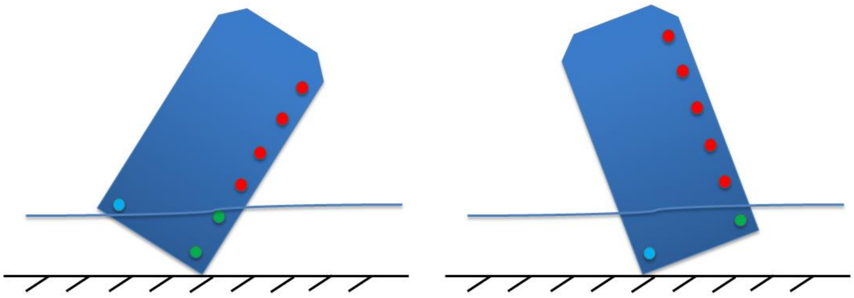


Figure 21 Sensor indications with tilted pump

When the pump is tilted to the right two of the sensors in the sensor array on the right side will indicate water whereas the sensor on the left side will be above water level and indicate a water level of zero. However if the pump is tilted in the other direction only one sensor in the sensor array will indicate water wheras the sensor on the left side will be submerged and indicate corresponding water level. This results in deviant measurements for the same water level depending on pump position. If the pumps are lying down missindication could be even more severe.

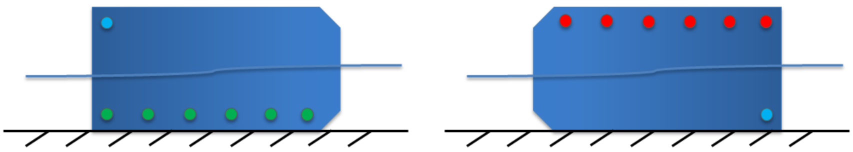


Figure 22 Sensor indication when pump is lying down

In the left case the sensor array will indicate that the pump is completely submerged whereas the continuous sensor will indicate a water level of zero. In the right case the sensor array will indicate a water level of zero and the continuous sensor will indicate corresponding water level of submersion. It is clear that depending on pump position sensor indications must be compensated for or sensors need to be placed in a different manner.

The problem could be solved by placing sensors around the pump at different heights in a similar way as proposed by Park and Kim as described in section 2.3.5. Logic can be implemented to determine tilt angle depending on which sensors are outputting water and air. Another option would be to include a compensating accelerometer. The accelerometer can indicate in what position the pump is and depending on submerged sensors the output can be adjusted after position.

3.4 Choice of sensor techniques

Sensor techniques were weighed against environmental affecting parameters as well as application variables. A decision matrix was put together to get an overview of how the different techniques performance is affected by different environmental factors in the operating environment. Other factors such as ease of implementation and cost are also presented within this matrix. Table 1 shows a fraction of the analysis matrix. Each field contains an estimate of how the sensors are believed to be affected. The complete matrix is found in Appendix C.

Table 1: Fraction of analysis matrix used as base for sensor decision.

Measurement technique	Temperature	EMC	Vibration/ Mechanical stress	Closeness of metal	Moisture/ Water remnants	Build-ups
Capacitive	low	-	low	medium	medium	high
Conductive	no	-	no	no	no	high

When investigating the affecting factors in relation to the sensor techniques it became clear that build-ups is the one parameter standing out that will affect the sensor performance to the biggest extent. Therefore this was an important factor when making a decision on which sensors to proceed with and is also the main factor the sensors were tested for. Other affecting factors are also of importance but were regarded easier to solve with e.g. design of the sensor.

As the sensors need to be integrated within the pump a rather simple solution is needed. A too complex or too fragile solution will not meet the requirements. Most techniques work of the principle of detecting water at one single point rather than performing continuous measurement, leading to a design where several sensors are placed in an array along the pump side as described in section 3.1. This means every single sensor element needs to be small to not take up too much space and it needs to be easy to implement in several discrete steps. Further the sensor element cannot be too expensive since several discrete measuring points are needed and every added measuring point will increase costs.

Investigating the optical fiber sensors there are several different techniques in the field. Studies show that they are often used within measurements in dams where the total measuring range is larger than for the pumps in mines. These sensors have had a resolution of around 1.5 dm, which is too large for this application. The optical fiber sensors studied are often expensive and quite complex to implement which is a drawback for the application at hand. Further they are fragile and sensitive to temperature changes.

When it comes to load cells there is very little literature about applications where this kind of sensor is used for water level monitoring. In general load cell sensor solutions are also quite expensive.

Optical sensors seemed to be a reasonable solution at first. However these kind of sensors are extremely sensitive for build-ups. If dirt builds up on the sensor it will be completely blind compared to other sensors, which might be gradually affected by build-ups but are still able to measure through thinner layers. Optical sensors can also be quite fragile which is not suitable for harsh environments with large mechanical impacts on the sensors. Further this kind of sensor is also quite expensive. As it needs to implemented in several discrete measuring elements the total cost will be high.

According to the literature studied, capacitive sensors seem to be the most commonly used sensor for the application of water level measurement. Capacitive sensors have been tested extensively since they are a robust and cheap solution. A drawback is that these sensors also will be affected by build-ups. Depending on the dielectric constant of the build-up and the thickness of the layer, water detection may be deteriorated but still possible to some extent. A solution to the build-up problem is presented by Khan et al. in section 2.3.1, where global fields are used for monitoring water level and local fields are used for detecting build-ups, which could be a possible implementation solution. Capacitive sensors can measure continuously from top to bottom of the pump if it is designed in a way that it stretches along the pump wall. It could also be implemented in discrete steps. If the build-ups do not occur evenly over the pump wall it might disturb the continuous design more than the discrete where build-ups might be detected more easily. Another article by Guirong and Shuyue describes a sensor which can be run in two modes, one for water level monitoring and one for measuring gradient of a tilted container. This might also be of interest for the pump application. Due to its robustness and low cost a capacitive sensor prototype was chosen for further tests. A solution working on the same principle as presented by B. Wang et al. described in section 2.3.1 was used.

The conductive sensor technique is a very simple solution. Implementing several discrete steps with sensor probes should be quite easy and not too costly. Further the sensor is not affected by temperature and the sensing probes are robust to mechanical impact since they are made of metal and no electronics need to be placed close to the probes. A drawback with this technique could be that there is a risk of build-ups completely isolating the probes. This will lead to that the circuit is not closed even when the sensor is submerged in water since current cannot flow through the isolating build-up. The solution proposed by An and An described in section 2.3.2 where each level segment consisted of pairs of electrodes where current could flow between them comes with the risk of moist build-ups short circuiting the probes even when placed in air. A better solution is presented by J. F. Kreutzer et al. as described in section 2.3.2 where the different sensing probes where short circuited to a ground probe. Since the conductive sensor is a non-complex solution, quite easy to implement this type of sensor was chosen for further tests with a design similar to the one by J. F. Kreutzer et al.

Pressure sensors are the one technique that on its own is believed most suitable to perform the water level measurement for the given application. It is able to measure water level continuously from the bottom of the pump to several meters above the pump. It is also less sensitive to different positioning of the pump since water pressure is the same in all directions. However it can fail indicating water level during low water if the sensor ends up being on the top side of the pump if it is tilted as described in section 3.3. Pressure sensors could also be affected by build-ups but maybe not to the same extent as other sensors. Further pressure sensors can be sensitive to changes in temperature, which is a drawback. Possibly a temperature sensor can be used for compensation. One reason pressure sensors have not been used more extensively for this application is high costs. Further the membrane is quite fragile and has not been able to withstand high pressure cleaning. However as technology has developed further new cheaper sensors are available in the market. A pressure sensor was included in further testing.

Regarding vibration sensors it was hard to find relevant literature for the application of water level measurement. However there is a wide range of tuning fork sensors on the market. Several of these also have a self-calibration function in order to compensate for build-ups, which is an advantage for the pump application. The drawback with current sensor designs however is that the tuning fork is sticking out. Components sticking out from the pump are easily breakable due to the careless handling of the pumps. One option could be to place the tuning fork vertically along the pump wall. However the current design of the tuning forks is also not optimal for implementation in several discrete steps. A flat version of a vibration sensor could be an option for implementation. Investigating the acoustic sensors they somewhat go hand in hand with the vibration sensors since they also work on the principle of waves with a certain frequency being dampened. Xylems early prototype test of a surface acoustic wave sensor for detecting water and oil leakage showed promising results. For this implementation a circular flat piezoelectric membrane was tested as a representation for a vibration sensor.

Calorimetric and temperature sensors are also a cost effective and simple solution. Measuring temperature is the easiest solution but might fail to detect water if the temperature in air and in water is the same. The advantage of a temperature sensor could be that it can be placed inside the stator house where it is more protected and measure temperature changes due to changing medium on the outside. However this will primarily be detection at one point and is harder to implement in discrete steps. Therefore a calorimetric sensor placed in discrete steps on the outside of the pump might be a preferable solution. Build-ups will probably affect this sensor too. A calorimetric sensor has been tested for water leakage within the pump and the same prototype was tested for the application of measuring water level outside of the pump.

3.5 Influence of affecting parameters

As build-ups were identified as the most influencing factors this was investigated further for the chosen sensors to proceed with. Primarily fat and limestone or concrete-like layers of drill-cuttings build up on the sensors. As the different sensors measure different physical parameters a table has been put together to show the values for those parameters for the different mediums to be detected, for water and air, as well as for the build-up materials to get an indication on how the sensor would react on build-up layers. Table 2 shows which sensor measures or is affected by which physical parameter.

Table 2: Overview over physical parameters measured by different sensors

Sensor	Density	Dielectric constant	Thermal conductivity	Heat Capacity	Electric conductivity
Pressure	x				
Capacitive		x			
Conductive					x
Calorimetric			x	x	
Vibration	x				

Further Table 3 shows the physical properties for different materials.

Table 3: Physical properties for different materials.

Medium	Density [kg/m3]	Dielectric constant	Thermal conductivity [W*m/K]	Heat Capacity [kJ/(kg*K)]	Electric conductivity [S/m]
H2O - freshwater	1000	80.4	0.6	4.19	0.01
H2O - salt water	1000	80.4	0.6	4.19	4.8
Air	1.2922	1	0.026	1	5.5E-15
Soil/clay		5-40	0,6-2,5	-	0,0001-0,01
Dry sand	1440	-	0,15-0,25	0.835	-
Wet sand	1922	20-30	0,25-2	-	-
Salt (NaCl)	2160	3,0-15,0	6.5	0.88	-
Coal powder	640	2,0-4,0	0,2-1,7	0.71	-
Limestone	1522	2,2-2,5	1,26-1,33	0.91	-
Oil/fat	889	2,2-5,3	0,15-0,20	0.4	1E-16

The density of most build-ups is closer to water than to air meaning large build-ups could lead to miss indication of water. A pressure sensor could be affected when the build-ups solidify and get so thick that the pressure of water and air cannot be sensed through the build-up. Meaning a pressure sensor is mainly affected by solidified build-ups. The dielectric constants of the build-ups are closer to air than to water. Thickness will probably matter. For a capacitive sensor wet dirt might be falsely interpreted as water. A capacitive sensor will mainly be affected by wet build-ups or if dry build-ups get thick enough. The thermal conductivity of build-ups is closer to water than air. However heat Capacity of build-ups is closer to air than water. Thermal conductivity of different mediums is what affects the calorimetric sensor the most. For a calorimetric sensor this would mean that build-ups could be falsely interpreted as water. The vibration sensor is believed to be affected mainly by the density of the material sensed. Through thinner build-up layers detection should still be possible. Further most build-up materials do not conduct current. The conductive sensor probably still works if wet dirt builds up on the sensor. However there is a risk of complete isolation if the build-up material gets thick enough. Conductivity of water highly depends on the salinity of water. As the mines contain a lot of minerals, water as such should work well as a conductor.

Table 4 shows how the sensors are believed to be affected by different build-ups in different measurement situations. The water column represents situations where the sensor is submerged and covered with build-up layers of different thickness. The air column represents situations where sensors are surrounded by air and covered with build-ups layers of different thickness. Further it contains cases of both moist and dried build-ups. For each sensor in each state a value is entered for what it is believed to indicate. The fields marked with red are risks for miss indication. At the bottom of the table the consequence of the miss indication is displayed.

Table 4: What sensors are believed to indicate in different conditions when affected by different build-ups

Medium	water			air					
Thickness of build-ups	1mm	2-3mm	4-5mm	1mm (dried)	1mm (moist)	2-3mm (dried)	2-3mm (moist)	4-5mm (dried)	4-5mm (moist)
Pressure	water	water	air	air	air	air	air	air	air
Capacitive	water	water	air	air	air	air	water	air	water
Conductive	water	air	air	air	air	air	air	air	air
Calorimetric	water	water	water	air	air	air	water	water	water
Vibration	water	water	water	air	air	air	air	water	water
Consequence	Risk for missing an alarm			Risk for false alarm					

All miss indications are severe; however a missed alarm will lead to more serious consequences than a false alarm. A false alarm will keep the pump running and can be compensated for with e.g. snoring detection.

4 Implementation

This chapter describes the sensor prototypes chosen to proceed with for testing. Further it includes design of tests and test environment to evaluate sensor performance in relation to affecting parameters.

4.1 Sensor prototypes

This section will present the different sensor prototypes that were tested. Specification information is retrieved from sensor datasheets.

4.1.1 Capacitive sensor

The capacitive sensor used is primarily developed by NOW Electronics for leakage detection within the pump house. It works on the principle of measuring capacitance in pF, which correlates to different dielectric constants of different mediums. The prototype comprises a FDC1004 4-Channel Capacitance-to-Digital Converter by Texas Instruments which can handle a scale range of ±15pF. Measurement resolution is 0.5fF. It can operate within temperatures between -40°C-125°C. The converter also includes shield drivers for sensor shields to reduce EMI. The sensor detects water at one single point and is to be implemented in discrete steps for water level measurement. When submerged in water the capacitance value increases. A capacitance limit value for water detection can be set to decide when the sensor is submerged and when it is surrounded by air. When the capacitance goes above the pre-set value the sensor will output at 20mA signal, otherwise it will output a 4mA signal. The sensor has a fixed hysteresis value of 0.3pF. The sensor circuit is placed within a 3D-printed housing. The housing is filled up with silicon or polyurethane to make it water proof. Figure 23 shows a picture of the sensor prototype with the sensitive area facing upwards.

Figure 23: Capacitive sensor prototype

The sensor is powered by 12V DC. Apart from the 4-20mA output the measured capacitance can also be monitored.

4.1.2 Conductive sensor

The conductive sensor is driven by an MIO 201 signal converter taken from another sensor solution used in other pump applications. The sensing probes and ground probes are made out of copper plates as seen in Figure 24. The converter powers the sensor probes with AC voltage. The probes are connected to the MIO 201 which converts the signals from the probes to a 4-20mA signal. The supply voltage of the converter is 15-30V DC. A total of ten sensing probes can be connected to the MIO 201. The supply voltage to the probes is 12V AC, 500Hz. The converter will output 4mA when in air and increase the output with 1.6mA for each probe submerged in water. When all probes are submerged the output will be 20mA. The probes can also be jumpered into groups if fewer level detection points are wanted.

Figure 24: Conductive sensor probes made of copper

The MIO 201 can be run within four different sensitivity modes depending on the type of liquid the sensor is supposed to detect. Sensitivity can be adjusted between *Extra Low, Low, Normal* and *High.* It can operate within temperature between 0-50°C.

4.1.3 Pressure sensor

The pressure sensor tested is a LT30FA from Pondus Instruments as seen in Figure 25, which is currently used in several other pump applications. The sensor has a measuring diaphragm of 316L stainless steel for high corrosion resistance. A piezoresistive sensor is connected to the sensed medium by the diaphragm. Pressure from e.g. water acts on the diaphragm and is transferred to the piezoresistive sensor trough pressure intermediate silicon oil. The oil completely fills the volume between the sensor and the diaphragm making the movement of the diaphragm very small with pressure changes. Analogue electronics convert the output signal of the piezoresistive sensor to a 4-20mA signal. The sensor can measure water depth up to five meters.

Figure 25: Pressure sensor.

The sensor is powered by 8-36 V DC. It can operate within temperatures between 0-80°C. The sensor measures absolute pressure and needs to be recalibrated over time.

4.1.4 Calorimetric sensor

The calorimetric sensor used is a prototype developed by Utronix for leakage detection within the pump. The sensor consists of two thermometer probes where on is heated. In air the probes will have different temperature and in water the heated probe will be cooled of resulting in the same temperature of the two probes. When in air the sensor outputs 4mA and in water it outputs 20mA. The sensor is powered by 12V DC. Figure 26 shows a picture of the calorimetric sensor.

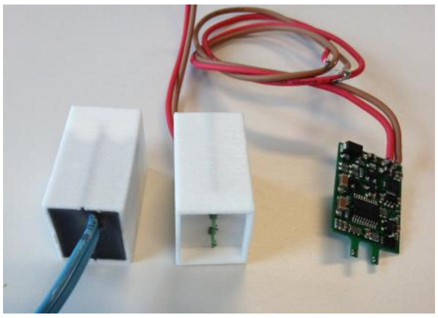


Figure 26: Calorimetric sensor prototype.

The current design with two spikes sticking out is not optimal for the given application since all parts sticking are more fragile. Folding the probes 90 degrees and placing them along the pump side would have been more suitable.

4.1.5 Vibration sensor

The vibration sensor prototype consists of a piezoelectric membrane installed in 3D-printed holder to water proof the cables. The sensor was initially designed as a flow meter where two sensors are placed with a distance in between in a holder and the echo voltage was measured. For this application only one piezoelectric membrane is used. The sensor is driven by a 1.1MHz signal making it resonate at its resonance frequency. Figure 27 shows a picture of the vibration sensor prototype.

Figure 27: a) Vibration sensor prototype in holder, b) Piezoelectric component outside of holder.

When the sensor is submerged the amplitude will decrease. Monitoring the amplitude will indicate if water is surrounding the sensor or not. The sensor can operate in temperatures between 0-150°C.

4.2 Test environment

To get an indication of how the sensors will be affected by the pumping environment in a similar environment had to be created within a lab. This section will describe the test lab environment, how affecting parameters were modelled or represented, the mechanical parts, hardware components and the software for monitoring sensor data.

4.2.1 Hardware and mechanics

The primary thing the sensors were tested for is build-ups. Tests should be designed to be repeatable. However it is hard to standardize dirt. To resemble build-ups from the operating environment two types of materials were used. Margarine *(Lätta Orginal)* was used to resemble fat build-ups and sand filler was used to resemble dirt, clay and limestone. As it was of interest to investigate the effect of increasing thickness of build-up layers, build-ups had to be added to the sensor surface in an adequate way. To let build-ups occur over time by e.g. dipping the sensors in dirty liquid was not considered an option due to limited time. Instead different thick layers had to be able to be applied on the sensors and the thickness had to be measured in an appropriate way. In order to do this a sensor holder was designed in which each sensor was placed within a tight space were it could be moved up and down leaving adjustable space between the sensitive area of the sensor and contact point with the measured medium. The thickness of this space could be measured and filled up with different build-up material. The sensors were kept in position with a set screw. Figure 28 shows a model of the sensor holder and how sensor height can be adjusted within the holder to apply increasing build-up layers. The distance T defines the thickness of the layer.

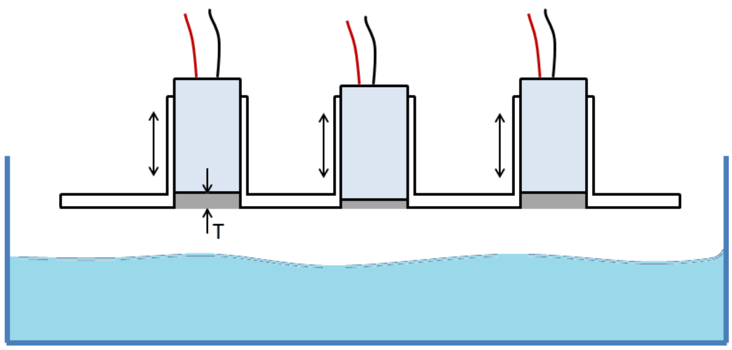


Figure 28: Model of sensor holder showing how sensors can be adjusted to add increasing layers of build-ups.

The sensor holder also fulfilled the purpose of submerging all sensors at the same time in order to get adequate measuring results from the sensor to compare their performance with each other and the actual state of water or air. Figure 29 shows a picture of the sensor holder with all sensors covered with sand filler build-ups.

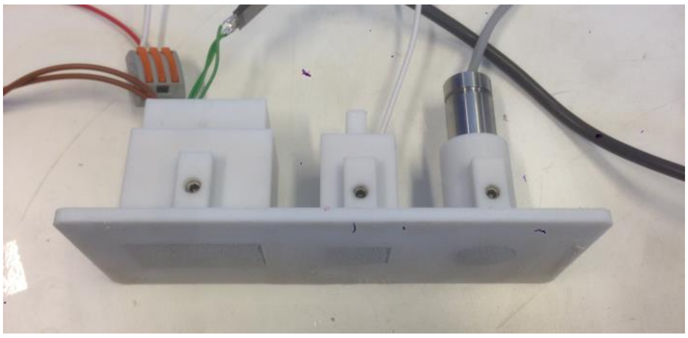


Figure 29: Sensor holder with sensors covered with sand filler build-ups.

In order to power the sensors and measure the output current of the different sensors a test circuit board was designed. A total of five connection points for plugging in five different sensors were added. The circuit board was connected to a DC power supply with adjustable voltage and current. The pressure sensor, conductive sensor, capacitive sensor and the calorimetric sensor all have an output of 4-20mA. The output currents were measured over resistors connected in series with the sensors. An Arduino Uno was used to collect the sensor data. Jumpers were connected to the analogue inputs of an Arduino Uno reading the voltage over the resistors. Further a temperature sensor, DS18B20, was connected to the Arduino to keep track of water temperature during the tests. Appendix D shows the schematics over the measuring circuit. The AC signal converter of the conductive sensor was powered directly by the power supply unit. The output pins of the converter delivering 4-20mA were connected to the sensor input on the measuring circuit. An overview of hardware components for the test environment is presented in Figure 30.

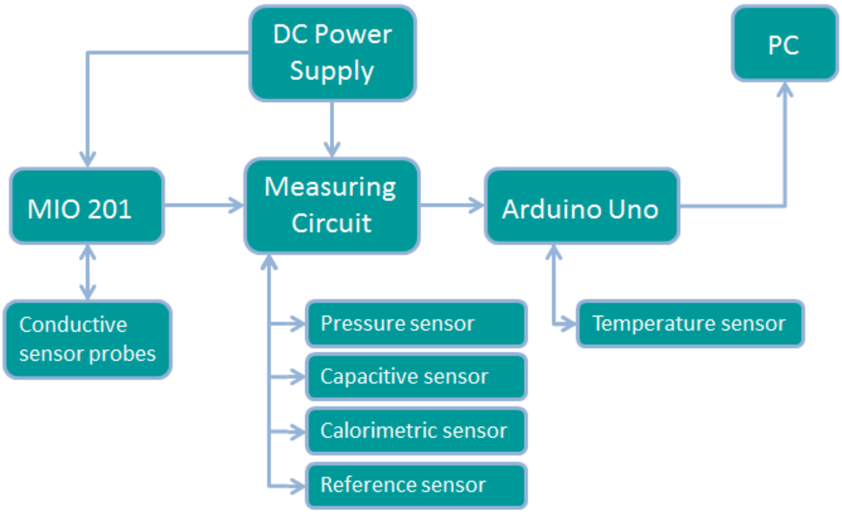


Figure 30: Overview of connections of hardware components.

The piezoelectric vibration sensor was driven by a 1.1MHz sine wave signal to vibrate at its resonating frequency. During the test phase it was connected to a signal generator. The amplitude was monitored with an oscilloscope.

4.2.2 Software

The Arduino Uno comprises an ATmega328P microcontroller with six analogue pins that can measure voltage from 0-5V. The AD-converter has a resolution of 10 bits resulting in ADC values from 0-1023. As the sensors have output signals of 4-20mA these signals had to be converted into voltage between the range of 0-5V. The relationship between voltage and current depending on the chosen resistor is given by ohms law, $U = I \cdot R$. In order to maximize U to 5V for the maximum current 20mA the optimal value of the resistor is given by equation (12).

$$\frac{5V}{0.020A} = 250\Omega \tag{12}$$

220 ohm resistors were used in the measuring circuit. This resulted in voltage signal ranging from 0.004A · 220 Ω = 0.88V to 0.020A · 220 Ω = 4.4V. The smallest increment the Arduino is able to detect is given by equation (13).

$$\frac{5V}{1023} = 0.0049V \tag{13}$$

To read out the output currents from the sensors the ADC value read by the Arduino was translated back into current value according to equation (14).

$$A = \frac{5V}{1023 \cdot 220\Omega} \tag{14}$$

The sensor outputs were measured every 500ms and were outputted to the serial monitor. In order to log the sensor data during a test, the program Exoterm was used to save the sensor data into text files.

Apart from the 4-20mA signal the capacitive sensor also has an output of the measured capacitance value corresponding to the dielectric constant of the surrounding medium. The capacitance value was monitored by a terminal program. Through this interface the alarm level for water detection could be set in order to adjust the 4-20mA output.

4.3 Testing

The purpose of the testing is to test the sensors simultaneously in different conditions and then evaluate the sensor results individually to see how each sensor is affected during different tests. The sensor data can then be analysed to see how the sensor data could be fused with algorithms and logic to achieve a more reliable result.

The final solution was supposed to monitor water level. However four of the five sensors tested work on the principle of detecting water level at one point and are to be implemented in several discrete steps. As the detecting process is the same for each level the sensors were tested for water detection at one point. For the conductive sensor the probe inputs were jumpered in a way that output in air was 4mA and output in water was 13.6mA. The sensor holder with the sensors was submerged and taken out of water continuously in a water tank at a water depth of four centimetres. As the pressure sensor measures continuously it outputted the current corresponding to air pressure when in air and the current corresponding to water pressure at 4cm depth when submerged.

Further the pressure sensor was tested individually at different water depths to evaluate how the continuous measurement was affected in different conditions. As the vibration sensor was driven by a signal generator it was not connected to the measuring circuit. It was tested individually but for the same conditions as the rest of the sensors.

Firstly the sensors were tested in clean condition with no build-ups added to the sensor surface. Secondly the sensors were tested with fat and sand filler build-ups. Increasing layers of build-ups were applied to the sensors. The sensors were tested for 1-5mm build-up layers increasing the thickness of the layer with 1mm for each test. Figure 31 shows the pressure sensor with a build-up layer of fat to the left and of sand filler to the right. In the photos the sensors are moved forward outside of the holder to show the thickness of the build-ups. During testing the sensors were placed within the holder with the outer surface of the build-up in line with the holder surface. During each test the sensors were submerged 20-30 times. A typical cycle of submersion was ten seconds in air and five seconds in water.

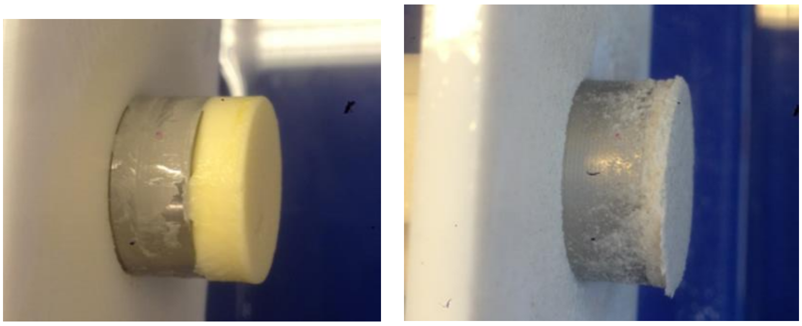


Figure 31: Pressure sensor with build-up layers of fat and sand filler.

Tests were performed both with moist sand filler when it was freshly applied and with dried sand filler that had solidified on the sensor surface in order to resemble both wet dirt and solidified build-ups from the mines. Figure 32 shows a picture of the dried sand filler build-up compared to an actual lime stone build-up from a pump in a mine.

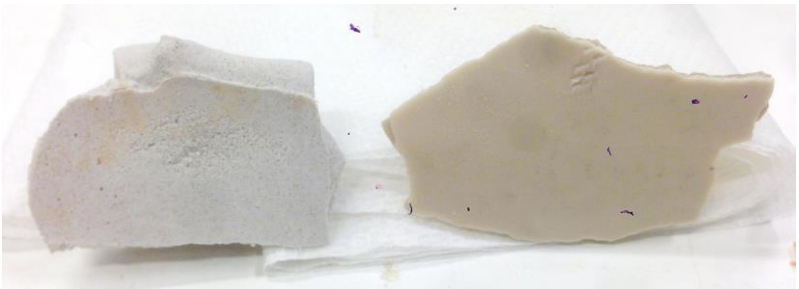


Figure 32: Dried sand filler build- up and lime stone build-up from mine.

The capacitive sensor was tested by submerging it both inside and outside of the sensor holder in order to identify if the design of the holder affected the result. The first capacitive prototype sensor was filled up with silicon. To improve sensitivity another prototype was filled up with polyurethane. Both sensors were tested to compare results. Further the sensors were dipped in water based furniture coating to investigate if it made the sensor more robust. The sensitivity levels of the signal converter for the conductive sensor were changed in order to see for which sensitivity the sensor performed best. A reference pressure sensor was used during all tests to monitor the actual state of water and air. Temperature was kept constant during each test at approximately 17°C.

5 Results and Analysis

This chapter presents the results from the tests of the sensors. Further it includes analysis of the data and an implementation of support vector machine models to compare output results with non-fused data.

5.1 Test results of sensors

Results from tests in different conditions are presented below.

5.1.1 Clean sensors

Calorimetric sensor

Initially the calorimetric sensor indicated water during all submersions and indicated air again after being taken out of water. The output current goes high when submerged and goes low when in air. When submerged the sensor indicates water immediately and when taken out of water and placed in air it continuous to indicate water for approximately 6 seconds before it indicates air again. After several test rounds the calorimetric sensor continued to indicate water in air for as long as one minute.

Pressure sensor

The Arduino initially outputted values below 4mA for the pressure sensor. Examining of the measuring circuit showed that the resistance over the resistor in series with the analogue input pin a0 was 170 Ohm. Recalculating output current resulted in proper values. The pressure sensor indicated water during all submersions and indicated air again after being taken out of water. Output current is proportional to pressure and water depth. Response time for indicating water and air is the same as for the reference sensor. Figure 33 shows the output current of the pressure sensor being submerged at different water depths. Water depth was changed from 17cm to 7cm in steps of 2cm.

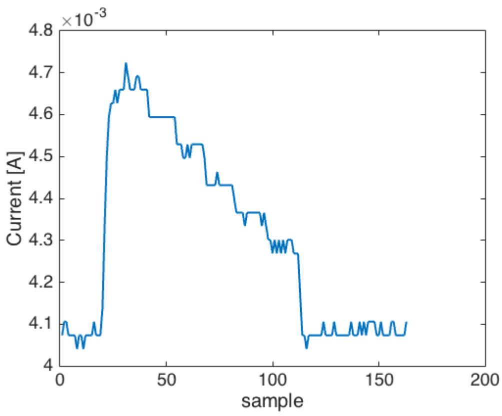


Figure 33: Pressure sensor output at different water depths.

The output current changes with 0.07mA per step meaning the resolution of the sensor is approximately 0.035mA per cm.

Capacitive sensor

The capacitive sensor indicated water during all submersions and indicated air again after being taken out of water. For the capacitive sensor both output current and capacitance is monitored. Indication of water and air is approximately 1 second slower than the reference sensor. Figure 34 shows a graph of sensor output during one submersion. The capacitive output is compared to the mA output where the y-axis displays pF and the values for the mA output is normalized to 1 and 0, water and air. Water alarm level is set to 2.5pF.

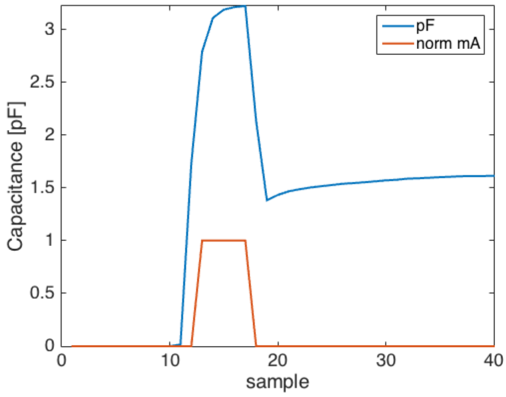


Figure 34: Output current and output capacitance for capacitive sensor.

In total four different capacitive sensors were tested and compared. Two were filled up with silicone and two with polyurethane to water proof the circuit boards. Figure 35 a) shows the comparison between the capacitive outputs of different sensors when submerged in water (outside of the sensor holder). Sensor 1 and 2 are filled with silicone and sensor 5 and 9 are filled with polyurethane. The graph shows that the capacitance values do not go back to zero when the sensors are taken out of water. When the sensors are dried off, the value returns to zero. Figure 35 b) shows the desirable output when submerged and taken out of water again.

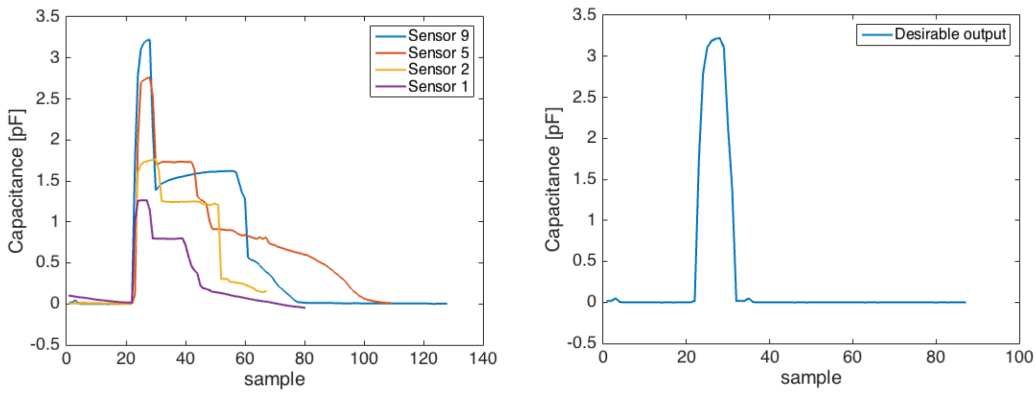


Figure 35: a) Capacitance output during one submersion for four different sensors. b) Desirable output

Capacitive sensor 5 was dipped in coating to investigate if it was more robust to water remnants on the surface. After the first submersion of the coated sensor the capacitance value went all the way down to zero directly when taken out of water. After a few submersions however the sensor showed similar output results as in Figure 35. Further the output values were compared between placing the sensor within and outside of the sensor holder to see if the holder affected the output values. Figure 36 shows the result for sensor 9 during one submersion.

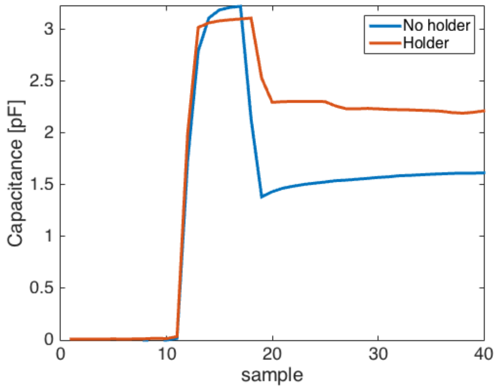


Figure 36: Capacitance output for submersion in holder and outside of holder.

To avoid water remnants on the sensor surface and in the sensor holder the sensor and sensor holder was covered with tape. This resulted in a less sensitive sensor and lower capacitance values in water, approximately 1.4pF compared to 3.2pF for sensor 9. However when taken out of water capacitance returned to 0.1pF immediately.

Conductive sensor

The conductive sensor indicated water during all submersions and indicated air again after being taken out of water. The output current goes high when submerged and goes low when in air. Indication of water and air is approximately 1 second slower than the reference sensor. Testing different sensitivity levels of the AC signal converter for conductive sensor showed that normal sensitivity works with distances up to 20 cm between sensing probes and ground probes and the high sensitivity is required to work over larger distances than 20cm.

Vibration sensor

The vibration sensor indicated water during all submersions and indicated air again after being taken out of water. The water dampened the amplitude, which decreased with 0.5 V when submerged.

5.1.2 Sensors covered with fat build-ups

Calorimetric sensor

Even with thin layers of fat the calorimetric sensor had trouble indicating the right medium. Fat build-ups led to false indications of water in air. Even after removing fat remnants the sensor continued to falsely indicate water in air. No further tests were performed with this sensor.

Pressure sensor

The pressure sensor was not affected by fat build-ups. Water detection was possible for all thicknesses of fat layers. Resolution was the same as in clean condition. Figure 37 shows the output of the pressure sensor submerged at different depths, starting at 17cm and decreasing the depth in 2cm steps until 7cm and then taken out of water. The blue line shows the output of the clean sensor and the orange, yellow and purple line show the output for different thickness of fat layers. Sensors are not submerged at the same time resulting in lines not coinciding at the x-axis.

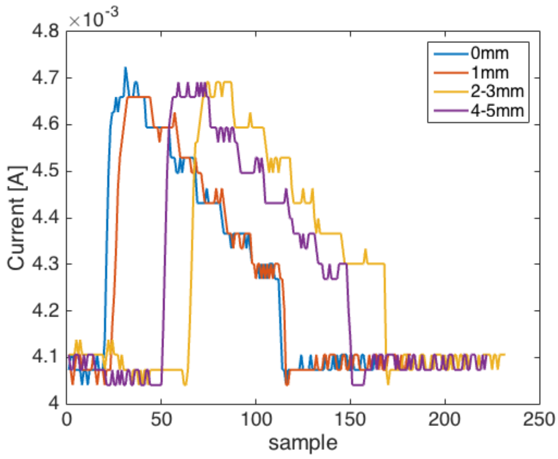


Figure 37: Pressure sensor output for increasing fat layers.

Capacitive sensor

The capacitance range between water and air decreased with increasing fat layers. The capacitance value in water decreased with increasing fat layers and the capacitance value in air increased with increasing fat layers. If the capacitance range between air and water goes below the hysteresis value of 0.3 pF, water detection with the 4-20mA output will not be possible. Figure 38 shows how the capacitance output changed for sensor 9 with increasing fat layers. The x-axis shows the thickness of the fat layer. The top blue line represents the capacitance value in water and the lower orange line represents the capacitance value in air. The black line shows a proposed water alarm level for the capacitance and the dotted black line represents the hysteresis level. The range between water and air is larger than the hysteresis value in all cases. For adjusted alarm levels water detection is possible with mA output in all cases. However the graph indicates that there is no common alarm level that would enable water detection with mA output for all cases.

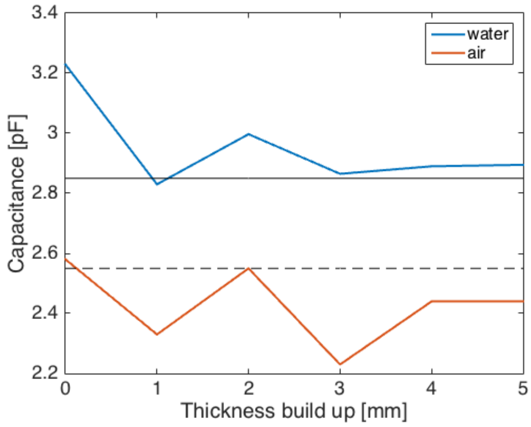


Figure 38: Capacitive range changing with increasing fat layers.

Conductive sensor

The conductive sensor was completely isolated even by thin fat layers and could not distinguish between air and water. The sensor indicated air even when submerged in water.

Vibration sensor

The amplitude of the vibration sensor was dampened even by thin fat layers resulting in water detection not being possible. Figure 39 shows the output for the vibration sensor covered in 1mm fat during two submersions compared to the submersion with a clean vibration sensor. The blue line shows the output of the clean sensor and the orange line the output of the sensor with 1mm fat build-up.

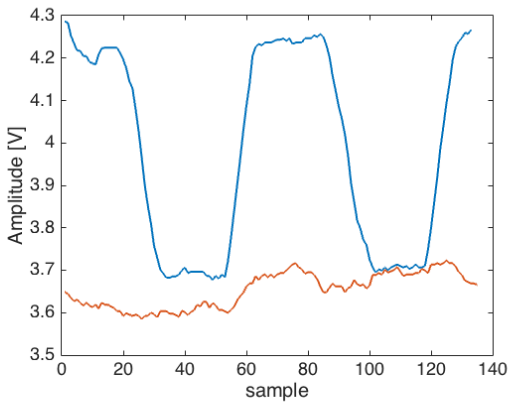


Figure 39: Vibration sensor covered with 1mm fat compared to clean vibration sensor.

5.1.3 Sensors covered with sand filler build-ups

Pressure

The pressure sensor was barely affected by moist sand filler build-ups. Water detection was possible for all thicknesses of moist sand filler layers. Resolution was the same as in clean condition. In cases with thicker sand filler layers the pressure sensor hade some higher output spikes when submerged in water. Figure 40 shows the output of the pressure sensor submerged at different depths, starting at 17cm and decreasing the depth in 2cm steps until 7cm and then taken out of water. The blue line shows the output of the clean sensor and the orange, yellow and purple line show the output for different thickness of moist sand filler layers. Sensors are not submerged at the same time resulting in lines not coinciding at the x-axis.

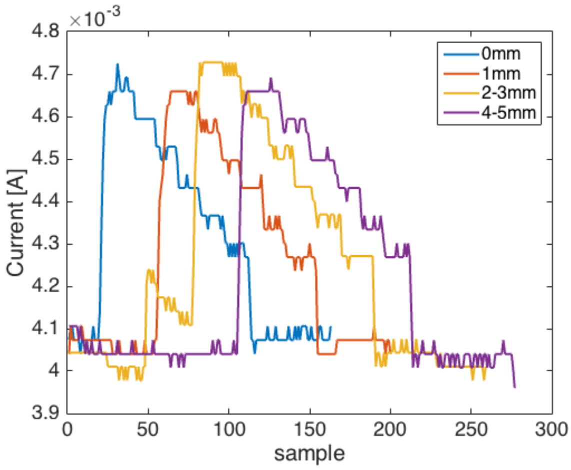


Figure 40: Pressure sensor with increasing layers of moist sand filler.

With dried sand filler the pressure sensor showed inconsistent behavior. Figure 41 a) shows a graph over sensor output during six submersions when covered with 1mm dried sand filler. The first two submersions are not detected. During the last four submersions sensor output increases. Figure 41 b) shows a graph over sensor output during seven submersions when covered with 5mm dried sand filler. When in air (left half of the graph) the sensor output is below 4mA, which is a sign of malfunction of the sensor. After the first submersion the sensor output returns to 4mA. During the following submersions a slight increment in pressure is visible. Repeated tests with longer drying time of the sand filler resulted in no detected submersions through thicker layers of solidified sand filler.

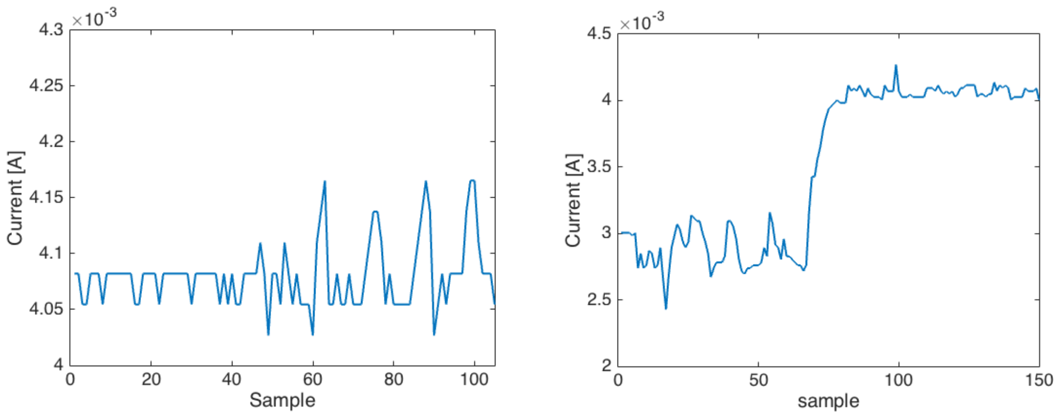


Figure 41: a) Pressure sensor output with 1mm dried sand filler, b) Pressure sensor output with 5mm dried sand filler.

Capacitive

Figure 42 shows how the capacitance range between water and air decreases with increasing thickness of sand filler layers. The x-axis shows the thickness of the fat layer. The top blue line represents the capacitance value in water and the lower orange line represents the capacitance value in air. The black line shows a proposed water alarm level for the capacitance and the dotted black line represents the hysteresis level. The range between water and air is larger than the hysteresis value only for 1mm layers of moist sand filler. For thicker layers of build-ups water detection is not possible with mA output.

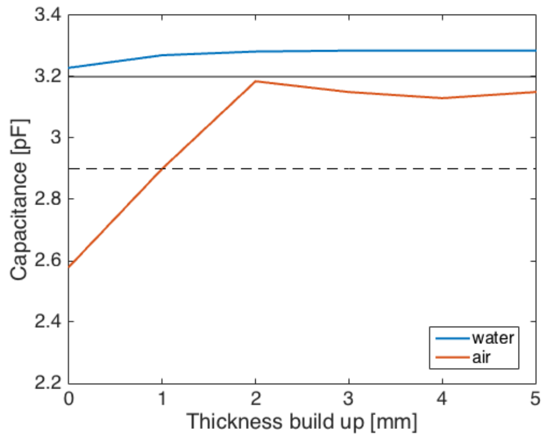


Figure 42: Capacitive range changing with increasing sand filler layers.

With dried sand filler the capacitive sensor showed inconsistent behavior. Figure 43 shows sensor output during six submersions. Capacitance value increases with each submersion and does not decrease when placed in air.

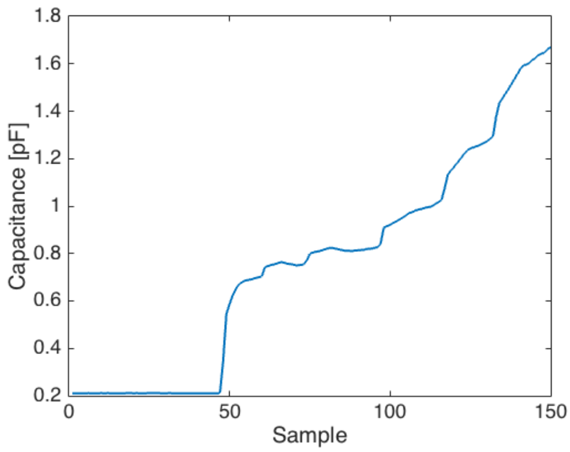


Figure 43: Capacitive sensor output covered with 3mm dried sand filler.

The sand filler gets moist when coming in contact with water, which affects the capacitance. For each submersion the build-up gets more and more moist leading to the increased capacitance during each submersion. This would not be the case for e.g. a solidified lime stone build-up. In order to see if the capacitive sensor can sense different mediums through solidified sand filler build-up a finger was placed on the sensor. Figure 44 shows sensor output when a finger is placed on the sensor two times for different thicknesses of solidified sand filler layers.

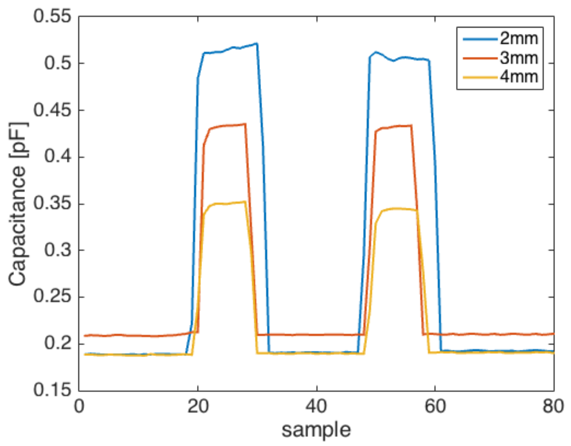


Figure 44: Capacitive sensor output for finger and air through different layers of solidified sand filler.

The range between capacitance in air and finger decreases with increasing build-up layers. For a 2mm thick sand filler layer the range is approximately 0.3pF, the same as the hysteresis. Further the sensor was placed 1mm from the water surface to see if water could be detected. Capacitance increases with 0.05pF.

Conductive

The conductive sensor managed to distinguish between water and air for all thickness layers of moist sand filler.

With build-ups of dried sand filler the sensor probes get isolated. Figure 45 shows the output of the conductive sensor covered with 1mm of dried sand filler (orange line) compared to a clean pressure sensor used as a reference sensor (blue line). The sensors were submerged 14 times.

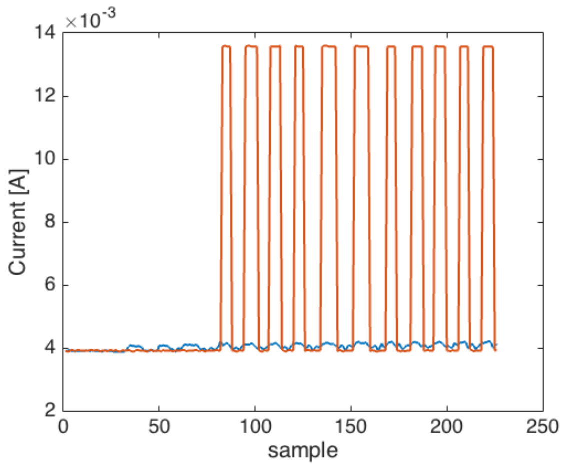


Figure 45: Conductive sensor output covered with dried sand filler.

The conductive sensor misses to indicate water during the three first submersions. After some time in water the sand filler gets moist enough to conduct current.

Vibration

The sand filler dampens the amplitude of the signal. When submerged a slight change in amplitude can be identified. Figure 46 shows the output for the vibration sensor covered in 1mm moist sand filler during two submersions compared to the submersion with a clean vibration sensor. The blue line shows the output of the clean sensor and the orange line the output of the sensor with 1mm moist sand filler build-up. The sensors are not dipped at the same time, thus dips in amplitude in the graph occur at different sample time.

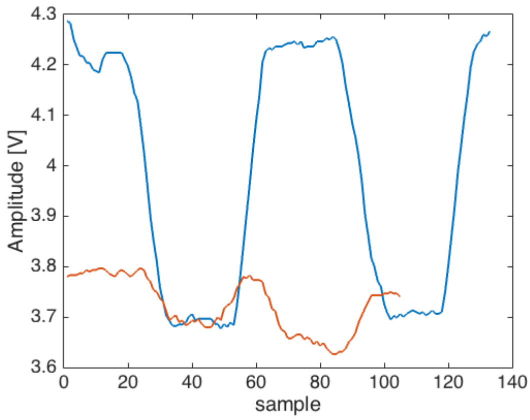


Figure 46: Vibration sensor covered with 1mm moist sand filler compared to clean vibration sensor.

5.2 Analysis of sensor performance

The calorimetric sensor prototype and the vibration sensor prototype were highly affected by build-ups and water detection was not possible even with thinner build-up layers.

The pressure sensor was affected the least by build-ups. With fat and moist sand filler build-ups performance remained almost the same as in clean condition. With dried sand filler layers however water detection was deteriorated. During tests with dried sand filler the sensor is not able to detect water during the first submersions. When the sand filler gets moist, detection is possible again since the build-up surface gets softer and pressure can reach through to the sensitive membrane of the sensor. Further the sensor output went below 4mA in some cases after the sand filler had solidified which indicates the sensor is malfunctioning. The first pressure sensor tested was permanently damaged after applying several layers of sand filler, which also indicates its fragileness. It is not certain whether it was the build-up itself or if scraping it off with a metal tool caused the damage.

The capacitive sensor is affected by all build-ups to some extent. Covered with fat the range between water and air is larger than the hysteresis value, which makes water detection possible with adjustable alarm level. When applying moist sand filler however the range decreases to as low as 0.1 pF which complicates water detection. Investigating the sensor output during submersions with dried sand filler the capacitance increases with each submersion. This is due to the sand filler getting moister for each submersion since the water penetrates the sand filler and transfers closer and closer to the sensor surface. The tests with sensing a finger through a solidified build-up give an indication of how the sensor would behave with a solidified build-up that does not get moist but where the water runs off the surface when taken out of water. In this case water detection might still be possible with the capacitive sensor. However it is clear that the sensitive range decreases with increasing thickness of layers. The capacitive sensors filled with silicone are less sensitive compared to the ones filled with polyurethane due to two reasons. Polyurethane has higher electric permittivity and silicone is more viscous resulting in inferior filling around the circuit boards causing air bubbles to stick between the sensitive board and the sensor cover.

The conductive sensor is completely isolated by fat build-ups. For sand filler build-ups water detection was possible for all thickness layers as long as the sand filler was moist enough to conduct current. When the sand filler dries, the probes are isolated and water detection is no longer possible. During tests it was assumed that sensing probes and ground probes are not placed in vicinity of each other. If this is the case and moist build-ups occur connecting the sensing probes to the ground probe there is a risk of the conductive sensor to falsely indicate water in air until the build-up has dried.

Table 5 shows how many submersions were detected by the different sensors during tests in different conditions. For the capacitive output in pF a submersion was considered as detected when the range between water and air was >0.1pF. For the pressure sensor a submersion was considered as detected when the range between water and air was the same as in clean state, 0.03-0.04mA/cm.

Table 5: Detected submersions during tests in different conditions

Condition	Capacitive [pF]	Capacitive [mA]	Conductive	Pressure	Calorimetric	Vibration
Clean	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
1mm fat	100,0%	100,0%	0,0%	100,0%	0,0%	0,0%
2mm fat	100,0%	100,0%	0,0%	100,0%	0,0%	0,0%
3mm fat	100,0%	100,0%	0,0%	100,0%	0,0%	0,0%
4mm fat	100,0%	100,0%	0,0%	100,0%	0,0%	0,0%
5mm fat	100,0%	100,0%	0,0%	100,0%	0,0%	0,0%
1mm sand filler	100,0%	81,0%	100,0%	100,0%	0,0%	0,0%
2mm sand filler	61,9%	0,0%	100,0%	100,0%	0,0%	0,0%
3mm sand filler	63,2%	0,0%	100,0%	100,0%	0,0%	0,0%
4mm sand filler	52,4%	0,0%	100,0%	100,0%	0,0%	0,0%
5mm sand filler	72,7%	0,0%	100,0%	100,0%	0,0%	0,0%
1mm sand filler dried	0,0%	0,0%	0,0%	80,0%		
2mm sand filler dried	0,0%	0,0%	0,0%	50,0%		
3mm sand filler dried	0,0%	0,0%	0,0%	0,0%		
4mm sand filler dried	0,0%	0,0%	0,0%	0,0%		
5mm sand filler dried	0,0%	0,0%	0,0%	0,0%		

Compared to what results were predicted in section 3.5 thin layers generally affected the sensors to a larger extent than expected. Impact on sensor functionality was expected to increase more linearly with increasing build-up layers. Results indicate that there is a quite large deterioration step when applying 1mm build-ups compared to clean sensors. Increasing thickness of build-ups up to 5mm does not further deteriorate the sensors as much compared to the difference of 1mm build-ups and clean sensors.

5.3 Sensor fusion with support vector machines

As the conductive sensor, the capacitive sensor and the pressure sensor showed the best individual results, the sensor data from these three sensors was fused in order to investigate if a combination of the sensors would decrease the probability of misclassification. For the capacitive sensor the capacitance output data was used. For fusing the sensor data SVM models were implemented in Matlab. A SVM model is trained on a set of sensor data and can then be implemented to predict new classification on future sensor data. Initially several SVM models were trained and optimized for each condition the sensors were tested for. To validate the performance of the SVM models the collected sensor data was divided into training data and validation data. This can be done in different ways:

Cross validation – Means selecting a number of divisions the data is divided into. Each division is held out for testing where the SVM model is trained on all the data outside of the division and then tested on the data within the division. The average test error is calculated over all divisions. This cross validation method thus efficiently uses all the data in different sets to train the SVM model and gives a good estimation of the predictive accuracy. It is recommended in cases with small data sets.[3]

Hold out – Means selecting a percentage of the data as training data and the rest as test data. The model is trained on the training set and performance is validated on the test set. This method is recommended only for large test data sets.[3]

In this case cross validation of the data was used to estimate the performance of the models. To train a SVM model the Matlab function *fitcsvm* was used. Primarily the function takes X and Y as an input parameter, where X is a matrix comprising the predictor data of the sensors and Y comprises the class labels. In X each row represents one observation and each column represents one sensor. For each observation, Y contains the corresponding true class label of that observation, in this case -1 for air and 1 for water. A reference sensor used during all tests defined the values of Y. Further input parameters can be specified in order to improve performance of the SVM model. The linear kernel function was chosen in order to linearly separate the data classes. The standardize flag was set to make the software scale and center the columns in the predictor data by the weighted column mean and standard deviation. As the sensor data was of a non-separable case it allows misclassifications at a cost of a box constraint factor. Increasing the box constraint will increase weight of misclassification and lead to stricter separation. A box constraint factor of 1 was used for the implemented models.

Figure 47 shows an example of a scatter of a set of data points $X=[x_1,x_2]$ where x_1 are predictor values of the capacitive sensor and x_2 predictor values of the pressure sensor. The capacitance is plotted relative to the output current from the pressure sensor for

[3] Information retrieved from Matlabs internal documentation.

each observation. The colour of the data points is decided by the class label vector Y where blue represents water and red represents air. Support vectors from which the SVM model calculates the separating hyperplane are marked with circles. The hyperplane is presented in black.

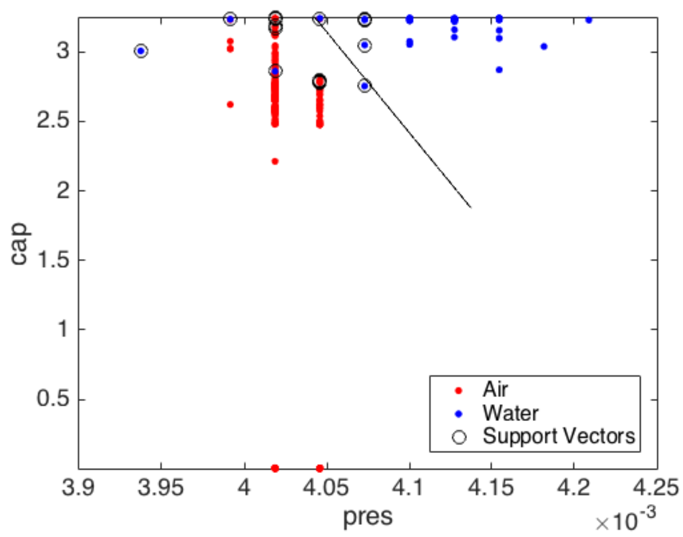


Figure 47: Scatter of capacitive and pressure sensor data with a separating hyperplane.

It is clear that no hyperplane can be found that separates all data points. All data points to the right of the hyperplane will be classified as water and all data points to the left of the hyperplane will be classified as air. The blue data points on the left side of the hyperplane show observations of water that are misclassified as air.

For each test condition i.e. clean sensors, fat build-ups and sand filler build-ups a SVM model was trained for each sensor individually, for sensors combined in pairs and for combining all three sensors. Performance for the different SVM models was compared. Table 6 shows the misclassification rate for individual sensors and for sensor combinations in all test conditions. The models with the lowest misclassification rate are marked in green. Among these, the models with the fewest sensors are outlined in black.

Table 6: Misclassification rate for different SVM models in different conditions.

Condition	Capacitive	Conductive	Pressure	Pressure Capacitive	Pressure Conductive	Capacitive Conductive	Pressure Capacitive Conductive
Clean	7,55%	4,49%	3,27%	2,04%	3,26%	4,49%	2,04%
1mm fat	7,24%	33,88%	1,91%	1,91%	1,91%	7,10%	1,91%
2mm fat	7,94%	35,59%	1,76%	1,91%	2,06%	7,94%	2,35%
3mm fat	5,97%	38,81%	1,33%	1,24%	1,24%	5,97%	0,75%
4mm fat	11,34%	35,26%	0,25%	0,25%	0,25%	11,08%	0,25%
5mm fat	11,04%	35,82%	1,79%	1,79%	1,19%	10,75%	1,19%
1mm sand filler	8,77%	5,22%	2,99%	1,88%	2,51%	5,22%	2,09%
2mm sand filler	14,06%	7,35%	3,73%	2,88%	5,75%	7,35%	3,83%
3mm sand filler	18,17%	8,06%	5,00%	3,87%	4,84%	8,06%	4,84%
4mm sand filler	18,92%	9,80%	4,05%	2,70%	4,39%	9,80%	3,72%
5mm sand filler	7,52%	11,19%	4,55%	3,85%	4,90%	10,14%	3,50%

Investigating the misclassification rates for the different sensors one has to consider the time ratio between when the sensors are placed in air and in water. The conductive sensor misclassification rate is around 35% when covered with fat. During these tests the sensor was submerged during 35% of the total test time, meaning no submersions were detected and misclassification could be seen as 100% when only investigation detected submersions. In the case with a 5mm fat layer the fused model with data from the pressure sensor and conductive sensor has less misclassification compared to a model where only the pressure sensor is used. However since the conductive sensor misclassifies all submersions as air this might be a misleading result.

Investigating the conditions with moist sand filler build-ups the misclassification rate for the individual sensors generally increases with increasing thickness of layers. However when looking at increasing fat layers the pressure sensor generally has less misclassification rate with increasing layers. This might be due to the fat dampening pressure spikes occurring during the submersion process of the sensor.

Further the output of the conductive sensor is of a discrete manner, outputting either high or low for water or air compared to the pressure and the capacitive sensor which have analog output with a range of values between water and air. This might affect the SVM model since the pressure and capacitive sensor can output values which are closer or further away from belonging to a class whereas the conductive output either belongs to one class or not.

As the condition of the sensors cannot be foreseen a model is needed to work in all conditions. Three more models were trained. One with data from clean state and fat build-ups, one with data from clean state and sand filler build-ups and one model trained on all data. Cross validation was used to estimate accuracy of the models. Table 7 shows the result.

Table 7: SVM models trained on conditions with fat, sand filler and all conditions combined, validated with cross validation.

Condition	**Capacitive**	**Conductive**	**Pressure**	**Pressure Capacitive**	**Pressure Conductive**	**Capacitive Conductive**	**Pressure Capacitive Conductive**
Clean + fat	10,46%	32,23%	1,54%	1,44%	1,54%	10,36%	1,63%
Clean + sandfiller	29,99%	11,71%	4,95%	4,95%	5,57%	11,71%	5,04%
All conditions	34,66%	21,11%	2,66%	2,66%	2,68%	21,11%	2,74%

Finally data from all conditions was divided into training data and test data where SVM models were trained with the training data and then tested on the test data to evaluate its performance. One SVM model was trained using the pressure sensor data, one with pressure and capacitive data, one with pressure and conductive data and one with data from all sensors.

Misclassification for testing the models on all test data was 3.04 percent. In all cases of misclassification the model indicates air instead of water. Looking at submersions in sequences all submersions are detected, however in some cases indication of water is delayed a bit which results in misclassified observations. As a response time of 5 seconds is acceptable this would be acceptable for the given application.

The SVM models trained on training data from all conditions were also tested on test data for each condition individually in order to see in which condition the model performed the best. Table 8 shows the results.

Table 8: SVM models trained on data from all conditions and tested on data of each condition individually.

Condition	Pressure	Pressure, Capacitive	Pressure, Conductive	Pressure, Capacitive, Conductive
Clean	3,33%	3,33%	3,33%	3,33%
1mm fat	3,33%	3,33%	3,33%	3,33%
2mm fat	0,00%	0,00%	0,00%	0,00%
3mm fat	0,00%	0,00%	0,00%	0,00%
4mm fat	0,00%	0,00%	0,00%	0,00%
5mm fat	3,33%	3,33%	3,33%	3,33%
1mm sand filler	3,33%	3,33%	3,33%	3,33%
2mm sand filler	3,33%	3,33%	3,33%	3,33%
3mm sand filler	3,33%	3,33%	3,33%	3,33%
4mm sand filler	6,67%	6,67%	6,67%	6,67%
5mm sand filler	6,67%	6,67%	6,67%	6,67%
All conditions	3,04%	3,04%	3,04%	3,04%

As performance was the same for the SVM models with fused data as it was with data of the single pressure sensor it can be concluded that adding the capacitive and conductive sensor do not decrease the misclassification rate for the SVM model when tested on data from all conditions. When investigating the data from tests with dried sand filler it was clear that the sensors had large troubles distinguishing between air and water. Figure 48 shows scatter plots of sensor data from all conditions including dried sand filler to the left compared data from all conditions excluding dried sand filler to the right.

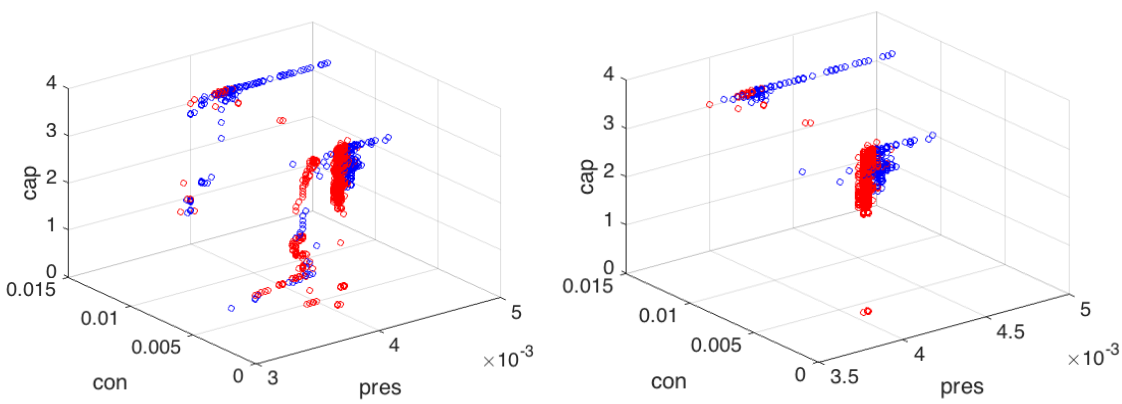


Figure 48: a) Scatter plots from data from all conditions, b) Scatter plot of data from all conditions except dried sand filler.

In the right graph it can be seen that a hyperplane can be found that at least fairly separates the blue and red data points with some slack for misclassification. In the left graph however no obvious hyperplane can be found that separates the data into two classes. Training a SVM model on the data in the left graph gives large misclassifications in all sensor conditions and distinguishing between water and air is not possible. Instead the models trained from data from all conditions except for dried sand filler was tested on the data from dried sand filler to investigate if any submersions could be distinguished. When the sensors were covered with 1mm solidified sand filler misclassification is 7.62%. All submersions were detected but the model also falsely indicated water when in air one time. Increasing layers of solidified sand filler caused the pressure sensor to output values below the 4-20mA range. For conditions of thicker layers of solidified sand filler submersions could not be distinguished by the trained SVM models.

6 Conclusion

Within this section the conclusions drawn from the thesis are presented. Individual sensor performance and combinations of sensors are evaluated. The combination believed most suitable for withstanding build-ups in harsh environment is presented.

Among the five different sensor prototypes tested the pressure sensor, the conductive sensor and the capacitive sensor are most suitable for water detection and level monitoring. Build-ups of different kinds are the factors that deteriorate different sensors the most. The vibration sensor and the calorimetric sensor were highly affected even by thin layers of build-ups and are thus not suitable for water detection. The pressure sensor individually outperformed the other sensors being able to monitor water level when covered with fat layers and moist sand filler layers. The advantage of the capacitive sensor is that water detection is possible through fat layer build-ups, however when covered in moist sand filler it falsely indicates water in air. If the hysteresis value is lowered detection may be possible if water alarm level is adjusted for moist sand filler condition. The conductive sensor on the other hand is able to detect water through moist sand filler layers but its disadvantage is being completely isolated by fat or solidified build-ups making water detection impossible in these conditions. Another risk with the conductive sensor is that it may falsely indicate water in air if the ground probe and the sensing probe are connected by moist build-ups. The advantage of the capacitive sensor compared to the conductive sensor is that the capacitive sensor is affected gradually by increasing build-ups whereas the conductive sensor gets completely blind. However the conductive sensor is the most robust solution regarding mechanical stress since sensor probes are made of metal and the electronics can be placed within the pump house. Since all sensors are deteriorated by solidified build-ups no single sensor solution was found that performs sufficiently in all stated build-up conditions. However the capacitive sensor is able to detect a finger through solidified build-ups, which gives an indication that the capacitive sensor can detect water through solidified build-up materials that do not imbibe water.

When combining sensors through SVM models for conditions with fat build-ups the model with fused data from the pressure sensor and the capacitive sensor had the lowest misclassification rate. Thus these sensors are most suitable to combine for this condition. However when training SVM models for moist sand filler conditions, the conductive sensor and the capacitive sensor do not contribute to lower misclassification rate. Further no model was found that could sufficiently distinguish between water and air for sensors covered in solidified build-ups.

Even though the SVM model is not improved in all conditions by combining the pressure sensor with other sensors there is an advantage of combining sensors simply by introducing redundancy to the system and having more sources to rely on. As the capacitive sensor shows indication of being able to detect water through solidified build-ups, where the pressure sensor fails, a combination of the two would be the most suitable solution for monitoring water level and handling the start and stop function of the drainage pump. Further the different outputs of the sensors could be combined and evaluated in order to identify in what conditions the sensors are.

Compared to the current solution with a mechanic variable level switch the new solution can keep track of water level in a more continuous manner instead of giving information on if water is above or below one specific point. Start and stop level can be adjusted through software instead of manually moving the mechanical level switch to a certain height. This will result in a more efficient way of controlling the start and stop function of the pump, leading to less energy consumption and less wear of the pumps. However it should be mentioned that in relation to robustness against build-ups, the current level switch is less affected than the sensors tested within this thesis.

7 Discussion and Recommendation

This section will discuss the outcome of the thesis. Limitations and methods are evaluated and possible improvements are presented. Validity of the result is discussed and propositions for continued work are made.

The initial standpoint was that different sensors, using different techniques, were believed to be disturbed by different factors and could therefore be combined to compensate for each other. Since it became clear that build-ups is the most deteriorating factor for all sensors, finding a logic combination became less intuitive. However since the tested sensor prototypes were affected differently by different kind of build-ups combining them was still motivated.

To evaluate the results and the conclusions of the thesis the limitations of the thesis project need to be considered. The sensor prototypes tested were taken from other application areas and were not designed specifically for the purpose of operating in mine environment. Therefore a conclusion of the calorimetric sensor and the vibration sensor not being suitable for monitoring water level is valid for these specific prototypes but not for the sensor technique as a whole. Comparing the tested vibration sensor to the tuning forks studied in the theoretical framework, build-ups occurring on the flat surface might dampen the sensor more than on out sticking forks since the build-ups on the fork can vibrate with the sensor. As the capacitive sensor was affected by different filling materials and by water remnants on the housing as well as the test sensor holder, results might have been different by using better water repellent materials and sealing of the sensor holder completely to avoid leakage. Further, testing the conductive sensor prototype was somewhat a black box approach with no knowledge of the analogue values measured by the AC signal converter but just monitoring the mA output of the sensor. Possibilities of increasing voltage might result in a higher robustness against build-ups. In general it should be investigated further how sensors could be designed in order to more efficiently withstand build-ups. Geometrical properties and water repellent materials could be areas of interest.

Regarding the test environment and test design it is hard to standardize build-ups of dirt from real environment. The build-up materials used during test resemble the real build-ups but are not a flawless representation. The main problem with the sand filler is that it is more porous compared to e.g. limestone and thus imbibes water when submerged. The moist sand filler can fairly represent moist dirt build-ups but for solidified build-ups it is not an optimal representation. During tests with solidified sand filler the first submersions during each test, before the sand filler got moist, give an indication of sensor behavior with solidified build-ups. However this resulted in less data collected in this condition compared to other test conditions, which also results in less reliability of the results in this condition. An option for applying build-ups to the sensors would have been to repeatedly dip the sensors in water containing materials from e.g. mines, letting real build-ups build up over time. This would have given more accurate results but would have been a time consuming process. Further the reference sensor used to monitor the real state of water and air was another pressure sensor. This might affect the result in favor for the tested pressure sensor since they work on the same principal. In general more tests should be conducted to further verify sensor performance.

The SVM models for fusing data give an indication on how reliability can increase when combining several sensors. However the SVM has some limitations. The SVM model classifies one observation at a time and does not take previous values into account, which is a drawback. Looking at submersions in sequences, all submersions might have been detected by the classifier model, but with some delay. The delay results in misclassifications of the model. However, since a response time of five seconds is acceptable the result could also be interpreted as 0% missed water detections. As the individual sensors also have different response times this further affects the training of the SVM models. Further the results of the SVM models indicated that in some conditions misclassification was lower when combining e.g. a pressure sensor with a conductive sensor even though the conductive sensor was not able to detect any of the submersions in the given condition. This is a risk when in this case the all-time low output of the conductive sensor happened to fit with the reference values of air. It would be of interest to investigate alternative ways of fusing the sensor data e.g. the Hidden Markov model, which also takes previous values into account. Further it can be discussed how one sensor could be used more as a build-up detector and adjust the other sensor according to current build-up condition. Another option would be to weigh sensor importance depending on current build-up situation and depending on which sensor is most reliable in the given condition. The SVM models within this thesis were only trained for water level measurement at one point. The next step would be to implement models for continuously monitoring water level over different depths.

In general water detection is more crucial than air detection since missing to start a pump will lead to severe consequences whereas missing to stop a pump will only lead to dry pumping and unnecessary wear and energy consumption. The sensor solution for water level monitoring could be combined with other functions at hand that detect dry pumping, in order to decrease dry pumping time. It can also be discussed what is affected first by build-ups, the water level sensors or other pump functions. If the pumps are in need of service sensors could be cleaned too.

Other improvements could be fault detection and self-calibration functions of the sensors. E.g. if values exceed the expected range an indication of malfunction of the sensor could be given. Further if build-up conditions are detected by the sensor, sensor alarm levels could be adjusted to fit the condition. If the sensor system indicates it is malfunctioning pump mode could be changed from listening to level sensors to using e.g. snoring detection.

When choosing which techniques from the theoretical framework to proceed with, several affecting parameters were taken into account. However the sensor prototypes were only tested in relation to the build-up parameter. In order to get a more complete picture of which sensors are suitable to operate in harsh environment tests for other affecting parameters are needed.

Further some interesting techniques were studied within the theoretical framework that could not be tested within this thesis since sensor prototypes were not available within the thesis time frame. One interesting approach is the design of a capacitive sensor by Khan et al., which utilises global and local electric fields to overcome build-ups. This technique should be investigated further to see if it could be a suitable solution for implementing in drainage pumps. New MEMS pressure sensors are also available on the market and could be of interest to investigate and test, to achieve a smaller and cheaper sensor solution compared to the pressure sensor used within this thesis.

Finally, regarding the validity of the conclusions of the thesis, mainly in relation to the conducted tests, it can be said that the tested fat build-up conditions resemble the real environment in the most coherent way. Thus the conclusions drawn regarding this condition are most valid. The solidified sand filler was proven to be a poor representation of e.g. concrete like limestone. Since it quickly absorbed water, data collection within this condition was also limited, making the conclusions drawn regarding this condition the least valid. The test condition with moist sand filler fairly represents moist dirt but it is hard to estimate how often the sensors will be covered with layers of moist dirt in an actual operating environment. It is somewhat difficult to compare results to current solutions investigated within the theoretical framework. Few articles described studies with tests in relation to build-ups in specific. Products were found on the market that stated to have self-calibration functions to adjust for build-ups but no documentation was found on how well they performed.

7.1 Future work

As discussed in the previous section there are some areas of interest for further investigation. Future work should focus on the following in order to improve performance of the investigated sensors and their combination.

- Further testing with build-ups. Preferably with solidified build-ups that in a more coherent way resemble actual build-ups in mines.
- Test against other affecting factors.
- Improvements of sensor prototypes e.g. different water repellent materials.
- Investigate other fusion algorithms
- Implementing algorithm for continuous level measurement.

In order to proceed with design and implementation of the integrated sensor solution the following is of interest.

- Further investigation of independence of orientation.
- Investigate fault detection and self-calibration functions.

- Where the real time sensor fusion algorithm should be implemented.
- Further investigate how and where the sensors should be placed and integrated in the pump.

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Appendix A – Application variables

Table 9 presents the application variables used for choice of sensor techniques.

Table 9: Application variables

Application variable	Explanation	Category
Accuracy	How accurate the measurements are	Performance
Resolution	In what increments water level can be measured	Performance
Response rate/timeliness	How fast the sensor can perform measurement	Performance
Reliability	How often sensor succeeds to deliver correct measurement data	Performance
Robustness	How well sensor can withstand affecting factors	Performance
Total life span	Total life time of the sensor	Life time
Operating time	How long the sensor can operate at a time (and between service	Life time
Power consumption	How much power the sensor solution consumes	Life time/cost
Ease of integration	How easy it is to integrate the sensor in the pumps	Implementation
Ease of operation	How easy it is for the user to operate the sensor	Implementation
Ease of maintenance	How easy it is to service the sensor	Implementation
Price	Price for components, software, integration, service etc	Cost

Appendix B – Requirement specification

Table 10 presents the requirement specifications the sensor solution needs to fulfil in order handle the task of monitoring water level.

Table 10: Requirement specification.

Requirement	**Specification**	**Requirement**	**Specification**
Temperature	Storage: -30 to +80ºC Operation: -10 to +100ºC Water temp: 0 to +70ºC	Resolution	5cm
Electromagnetic disturbance	Emission: According to EN 61000-6-3 (household). Immunity: According to EN 61000-6-2 (industry).	Response rate/timeliness	5s
Vibration	Normal: < 7,1 mm/s Extra ordinary - 50 mm/s	Size/Physical dimension	Not specified
Mechanical stress	Fall test in product: 4 directions to a concrete floor Fall test in packing or wrapping: 1 m to a concrete floor	Material	Withstand requirements above
Build-ups	Withstand build-ups of up to 5 mm	Mounting/Integration	Should be integrated in pump
Closeness of metal	Not specified	Power consumption	Not specified
Humidity	Rel. humidity <50% at +40º C Rel. humidity 10-95%, non cond (storage)	Principal	Sensor without moving parts
Moisture/Water surface tension	Not falsely alarm due to water drops remaining on sensor	Ease of implementation	Not specified
Water resistance	Water absorption < 3 %	Ease of operation	Not specified
Pump position	Measure water level independently of pump position	Ease of calibration	Not specified
Pumped medium	Handle water with 10-15 weight% percent of gravel and pH-vale of 5-8	Ease of maintenance/service	Not specified
Operating time	Run continuously for 3 months	Price/Cost	Not specified
Life span	2000h between service Total lifespan: 50.000 h at 55º C		
Altitude	Operating amplitude Max. 2000 m Transport altitude Max. 3000 m		

Appendix C – Analysis Matrix

Table 11 presents the analysis matrix used as a base for sensor technique choice. Estimates and numbers are explained below the table.

Table 11: Analysis matrix

Measurement technique	Temp	EMC	Vibration/ Mechanical stress	Closeness of metal	Moist	Water surface tension	Build-ups	Position of pump	Ease of implement-ation	Cost
Capacitive	low	-	low	medium	low	medium	medium	high	1	1
Conductive	no	-	no	no	no	no	medium	high	1	1
Load Cell	medium	-	high	no	no	no	-	high	3	3
Optical	no	-	high	no	no	medium	high	high	2	3
Pressure	low/medium	-	medium	no	no	no	low	medium	1	2
Vibration	low	-	low	no	no	no	low	high	2	1
Calorimetric	*	-	low	no	no	no	low	high	1	1
Temperature	*	-	low	no	no	no	low	high	1	1
Optical fiber	medium	no	high	no	no	no	medium	medium	3	3
SAW	no	-	-	no	no	no	medium	high	2	2

Explanations for environmental factor columns:

- no information
* special case (sensors can be affected during special circumstances)
no does not affect sensor performance
low can affect but may be negligible
medium more probable to affect but may be avoided by placement/design
high highly affects sensor performance

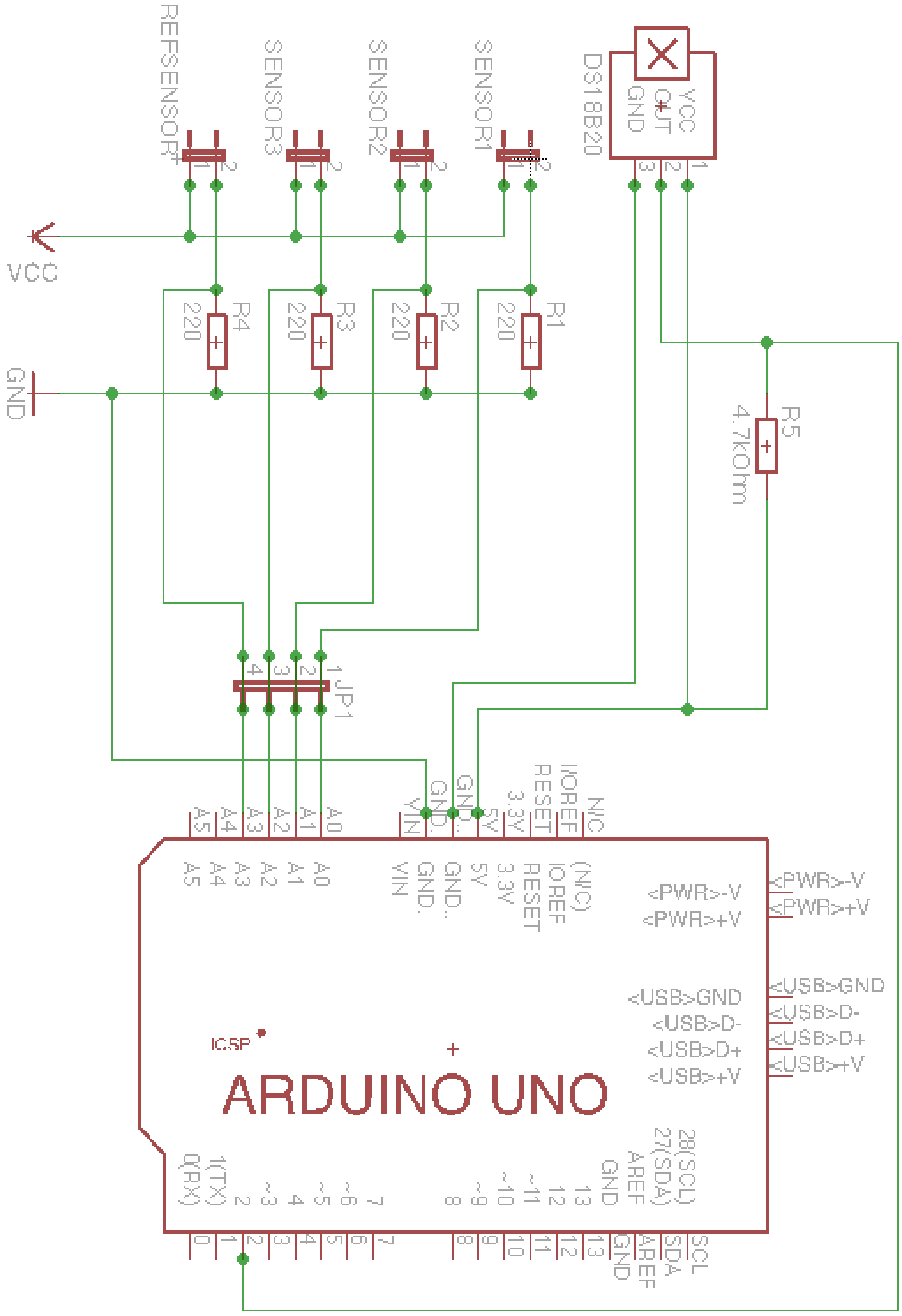
Number explanations for Ease of implementation column:

1 Easy
2 Medium
3 Complex

Number explanations for Cost column:

1 Cheap
2 Medium
3 Expensive

Appendix D – Measuring Circuit



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