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Abstract—**Due to European legislation, enforcing the monitoring of fish migration and bio-diversity in the aquatic ecosystem a cost effective system is required to evaluate the effectiveness of so-called fish friendly passages in waterways. Currently existing systems have limitations or are too expensive to use on a large scale. This paper proposes a system based on reconstructing a two-dimensional map of the resistivity in the passage which is achieved by measuring changes in potential and applied current on many electrodes. Both simulations and real world measurements are performed and evaluated. Both hardware and software are developed and the results, which show a good resolution considering the number of electrodes, are presented. Finally it can be concluded that although further development is required the developed system is a solid basis to develop a real time fish recognition system. The use of this new system will allow monitoring of fish count and migration patterns in places where this was previously not possible.**

I. INTRODUCTION

In the Netherlands, Flanders and Northern Germany there are a large numbers of pumping stations that are used to control the water level. These pumping stations use a large variety of pumping methods most of which are harmful to fish. In an aim to preserve, and in some cases restore, the fish population in these waters, special pumps and passages are constructed that allow the fish a safe passage around the pumping stations. Fish are steered away from the pump inlets and guided to the fish passages by making the entrance to the passages very dark and putting flashing lights near the inlets of the pumps. Fish prefer dark places over very bright places and will enter the passage instead of the inlet.

To evaluate the effectiveness of these systems it is required to be able to count the number of fish that pass through the system. In order to gain insight in migration patterns it is also required to determine the kind of fish, therefore only being able to count the number of passing fish is not enough and some information about the size and shape of the fish is required.

Common methods have been tested by others and reported that these methods do not work well in the Dutch environment. This is mainly because of the cloudiness of the water preventing camera systems from working effectively as is described in [8]. Providing extra lighting for camera's is not possible since this may scare the fish and make them avoid the fish passage. Another method uses high resolution sonar but the downside of this is the high cost, these systems cost more than one hundred thousand dollars [6] and also have their disadvantages, are discussed in section III. Making them unsuitable to use for large numbers measurement locations.

The lack of a suitable system justifies the development of a new system based on different techniques as described above. Clearly such a system has to be based on another method than optical or acoustical imaging. In addition it is important that the cost of the system will be kept as low as possible in order for the new system to be competitive with the existing methods. By implementing the new system it will be possibly to monitor fish count and migration patterns in places where this was not possible before, this will increase the knowledge in the effectiveness of fish passages but also in fish behavior in a certain region in general.

In section II related work and existing solutions and their characteristics are described, section III describes the concept for the new system. In section IV results of simulations are presented that give information on the physical behavior of the system and in section V and VI the development of the required hardware and software is described. In Section VII experimental results are presented that are performed with the system and the results are discussed, section VIII shows research into the production cost of the system, section IX describes future work and finally the results are compared with existing methods in section X.

II. RELATED WORK

Due to the increasing interest in the ability to count, recognize and classify fish there are already a number of experiments performed and methods developed. Most of these methods are based on using cameras with a vision recognition system that allows a computer to classify a fish as a member of a certain species. This classification can be performed purely by the shape of the fish as described in [1] and [2] or a combination of shape and colour as described in [3] where a reliability of 98% and even 100% for certain species of fish is claimed. These recognition tests were done on dry land and not in an actual fish passage. The same system can be used in an actual test setup when the water in the fish passage is clear enough. As described in [4] the way how colour is perceived depends on the composition of the water which needs to be corrected in order to compensate for this effect. In [2] is also described how occlusion can occur on a camera image which makes accurately recognizing a certain species of fish more difficult, especially when they tend to swim in groups.

Another approach that seems to provide good results is the use of special type of sonar. In [5] an experiment using this DIDSON sonar is described showing high resolution images of fish in fish passages. This method gives good results, the sonar units however are expensive and cost over one hundred thousand dollars per unit according to [6].

An alternative to counting fish is the use of a three-electrode resistivity measurement as described in [7] which uses two 'driven' electrodes that apply a alternating voltage that is picked up by a fish that passes the electrode in the middle. The phase detected on this electrode gives an indication about the direction of the fish which allows counting in a certain direction. It does not allow recognizing specific fish species.

Some of these methods have been simulated or assessed by [8] as part of a previous masters thesis which proved that it is very difficult to get decent results using optical methods for fish recognition. Even special setups with cameras that place restrictions on the environment do not seem to help enough for the cloudiness in the Dutch river environment.

III. THE CONCEPT

Due to the difficulty of using existing methods to count fish in waters in the Netherlands, due to very turbid waters, the system that needs to be developed cannot be based on optical image recognition. Also sonar is not preferred because of high cost.

An additional disadvantage of using a camera or sonar based systems is that one object can block the field of view to another object making the counted number of fish less reliable. This disadvantage can be partially overcome by adding a second camera of sonar system at 90 degree angle to the first one which reduces the chance on (partial) occlusion, an example of the described problem is shown in figure 1 where fish 4 will not be detected.

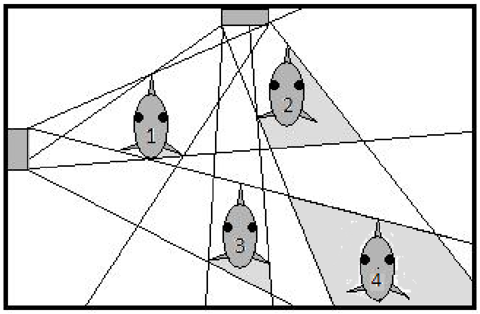

Fig. 1. (Partial) occlusion due to camera/sonar viewing angle

Because of these restrictions there is a need for a relatively cheap system that can work in turbid waters. This paper will describe a system that can create images based on cross-sectional resistance of the water in between the electrodes. Since fish have a lower resistance than the surrounding water the fish will show up as a drop in the resistance. By using many electrodes and measuring from different directions a two-dimensional image of the resistance can be created. In future versions capturing multiple of these images will provide a side view of the fish which can be used for recognition purposes. An additional advantage of this system is that there will be no occlusion, fish that are very close however can still be detected as one drop in resistance. If the resolution can be high enough the recognition algorithm should be able to compensate for this.

In order to be able to measure from multiple directions multiple electrode on each side of the fish passage, which is a square with sides of approximately 60 centimeters or a circular tube, are required. Each of the electrodes needs to be able to either measure or generate a potential to generate the required field for detecting resistance changes. The potentials of all electrodes have to be measured and sent to a computer for further processing. This processing involves reconstructing a map of the changes in the potentials and currents with respect to situations with and without a fish. To be able to cope with changing water conditions the system uses a running calibration and subtracts the average from the last measurement. Using the running calibration has the advantage that slow changes in the water composition that influence conductivity will not be seen in the measurement results, cloudiness of the water will have no influence at all as long as the conductivity does not change. Even when this is the case, it will be compensated by the running calibration. The resulting 'delta' values are used to make maps of both potential and resistance and these are combined to obtain the final result. The potential based reconstruction is performed based on the Laplace equation which takes the average of the adjacent potentials: $U_{i,j} = \frac{U_{i-1,j}+U_{i+1,j}+U_{i,j-1}+U_{i,j+1}}{4}$

Both the hardware and software required to build this system was designed and constructed and used to obtain experimental results which backup the simulated results.

Based on this description some functional requirements can be specified:

1) The system must be able to control multiple electrodes to perform the measurements.
2) Both current and potentials have to be measured.
3) Very small changes in current and potential have to be able to be measured.
4) A running calibration has to be performed to cancel out gradual changes in water composition.
5) Based on the measurements a two-dimensional map of the resistance has to be reconstructed.

IV. TWO AND THREE DIMENSIONAL SIMULATION

To control the measurements that are necessary to make a reconstruction of the cross-sectional resistance hardware needs to be developed. Since the requirements to this hardware were at this stage still unknown simulations were done and evaluated. Based on the results of these simulations it was determined to also do a small scale experiment to determine the amount of noise present in the system. Key factors necessary to establish the hardware requirements are:

- Behavior of the electric field
- Voltage change at the edge of the electric fields
- Current between the positive and negative electrodes

A. *Two-dimensional simulation*

A rough estimate of the feasibility can be made by constructing a two dimensional simulation and measure the voltage and the current between the positive and negative electrode. The first version of this simulation was performed using an excel sheet explained in [9] which is normally used for groundwater potentials, the behavior of this is the same as the behavior of an electric field in a given material and uses the Laplace equation to iteratively solve the system. In fact, before computer simulations were done groundwater potentials were determined by having a thin foil of a conductive material with electrodes tat applied a voltage. By measuring the voltage at a certain point the groundwater potential could be determined.

This excel sheet was extended to be able to work with different resistances at different places in the system compared to an equal resistance value everywhere. The original version used the basic Laplace equation which takes the average of the four surrounding fields. The extended version has a second sheet describing the resistances everywhere in the cross-section, a graphical representation of this extra information is shown in figure 2. In addition changes were made such that the edges of the simulated area are considered floating instead of a fixed potential by also using the Laplace equation at the edges.

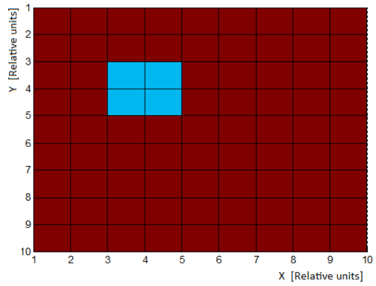

Fig. 2. Resistance map used to simulate electric field

This method was converted into a Matlab script which constructs a set of linear equations, based on the Laplace equation, which when solved provide information about the change in the electric field that will occur by the presence of a fish. Because of the lower resistance of the fish relative to the water there will appear an area in the electric field that has a relatively flat slope, as indicated in figure 3. Due to this change the potentials at the edge of the electric field will also change due to the Kirchhoff voltage law. It can also be observed that a change close to the electrode will result in a larger change in the potentials at the edge than a change in the middle since the slope in the middle of the field is already much flatter. This can be compensated by also measuring the change in the current applied by the electrodes and taking it into account in the reconstruction algorithm.

Evaluation of the simulation results showed that, depending on the position of the fish, the voltage levels can change by approximately 0.5 volt and the current levels by approximately 1 milliampere in case a voltage of 10 volt is applied between the electrodes. The voltage change is ratiometric to the applied voltage. Based on these results some small experiments with reconstruction algorithms were performed, the results of those are shown in figure 4

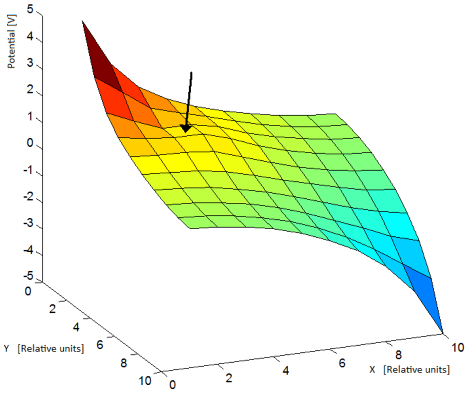

Fig. 3. Simulated electric field, with fish present

The advantage of algorithm ‘a’ in figure 4, which only multiplies currents measured in horizontal and vertical direction, is that it is very easy to calculate and therefore very quick. The disadvantage is that it can introduce artifacts that might show a resistance change in cases where there is none, this is due to the fact that it only measures in horizontal en vertical combinations of electrodes. Despite these artifacts it is useful for doing a preliminary detection, if the algorithm shows a resistance change a more complex algorithm can be used to extract more precise information. This is done with algorithm ‘b’ which also supports measuring in diagonal directions which results in more complex calculations but cancels out reconstruction artifacts. This algorithm calculates the path between the electrodes and takes the average resistance measured over all these paths that cross a certain field in the grid.

B. *Three-dimensional simulation*

The results obtained in the two-dimensional situation do not consider the fact that in reality the current can flow in all three directions. In order to analyze the effects of this extra dimension a new model was constructed in the Finite Element Method (FEM) application ‘Comsol’. This can be achieved by drawing the test setup and specifying the material properties. After designing the experiment a mesh will be generated which is used to solve the differential equations that are generated by Comsol. The solution is shown graphically, see figure 5. In figure 5 the electrodes marked with ‘+’ and ‘-’ are the electrodes that have respectively the positive and negative voltage applied. The downside of the Comsol simulation is that it takes almost two hours to calculate which makes it faster to measure on a small-scale experimental setup.

1) Electrode issues: From the simulations done with Comsol on the three dimensional model it was shown that due to the large amount of copper from the electrodes around the

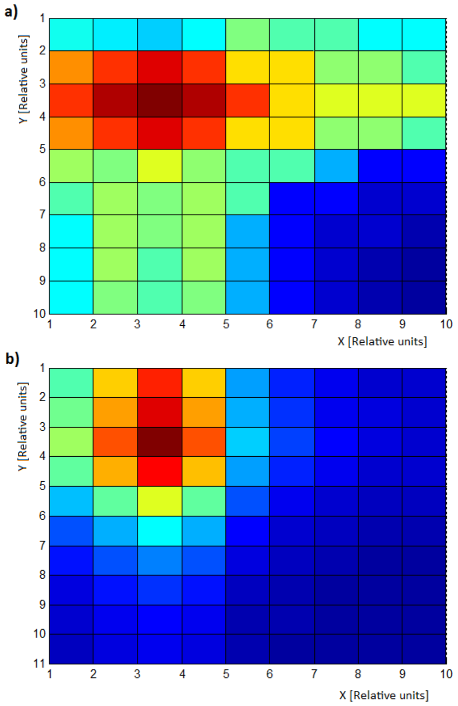

Fig. 4. Reconstruction results from two different algorithms

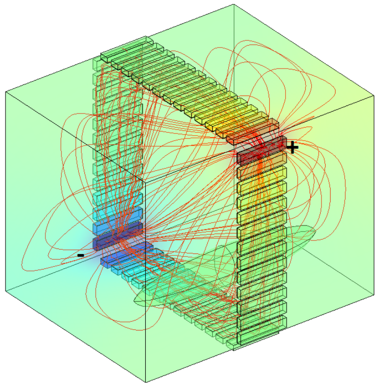

Fig. 5. Graphical result of the three dimensional simulation, the ellipsoid is a strongly simplified ‘fish’ with a higher conductivity than water

edge of the tube the current tends to flow mainly around the edges. This effect can be observed in figure 6 where the lines that indicate the flow of current group very close together indicating a strong tendency of the current to flow around the edge from electrode to electrode.

The tendency of the current to flow around the edges causes the measurements to be much less sensitive to changes in resistance closer to the middle of the tube. For this reason the electrodes had to be constructed from another material than copper, also the size of the electrodes was reduced to create more space between each electrode.

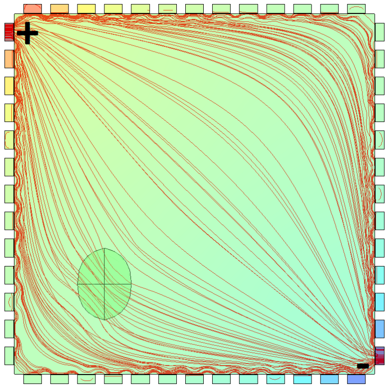

Fig. 6. Flow of current around the edges due to electrode conductivity

2) Electrode material: In order to choose a suitable material for the electrodes some materials were compared against their conductivities. The material with the conductivity the closest to the conductivity of water will disturb the measurements the least and will therefore produce the best results. Water has a conductivity between 0.005 and 0.05 Siemens per meter depending on the type and purity of the water. Possible electrode materials that were considered are:

Copper	$5.7 * 10^7$ Siemens/meter
Graphite	$3.0 * 10^3$ Siemens/meter
Pressed carbon fiber	200 Siemens/meter

Due to the much lower conductivity of the carbon fiber this will be the most suitable material to make the electronics from. In addition to the conductivity this material does not corrode which means that the lifetime is much longer and the electrodes will not pollute the water with copper-oxide which is poisonous to the ecosystem. The challenge arising with this material is that a good method needs to be developed to connect the wires to connect the wires to the carbon fiber.

C. Small scale experiments

The simulations provide good insight in the behavior of the electric field within the water and how this will reflect on the electrodes. However the simulation does not provide information about the noise level in the system. In order to determine this a simple three-electrode setup is used to determine this parameter, the setup is shown in figure 7. Two electrodes are used to provide the positive and negative potential and the other is measured with an 24-bit analog to digital converter connected through USB. The noise level of this circuit with the input shorted to ground is approximately 0.2 millivolt which will be used as a reference, a 40 volt potential was applied at the active electrodes.

The average noise level between two measurements proves to be 0.98 millivolt and the maximum noise level measured was 17 millivolt in 175 measurements. The maximum noise occurred only once during measuring and the other values are generally much smaller which indicates a peak that is possibly caused by an external influence. Since it is known from the simulations that a voltage change of approximately 0.5 volt can be expected this noise level would be easily low enough to detect smaller changes. The measured current was in the worst case 32 milliampere at 40 volts.

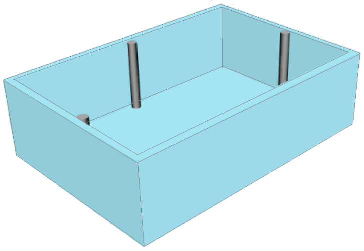

Fig. 7. Setup of the small scale experiment with three electrodes

D. Requirements on the system

The simulations helped defining some properties of the system but due to limitations in simulation a real world experimental setup needs to be developed. This system needs to have a certain functionality which can be defined as follows:

- The system must be able to control multiple electrodes to set them to either the positive, negative or floating voltage.
- For each electrode the potential on that electrode has to be measured.
- The current that is applied must be measured.
- Since it is not yet known how many electrodes will eventually be needed the system must be scalable.
- The measurements must be gathered and sent to a computer for further processing.
- A reconstruction algorithm must reconstruct a two-dimensional cross-section of the resistance between the ‘ring’ of electrodes.

V. HARDWARE DESIGN

The hardware will provide a platform to gather measurements and send them to the computer. Since not all characteristics are completely determined before doing experiments the hardware needs to be flexible in both the current and voltage that can be applied. This allows to scale the voltage to what proves to be necessary in the experiments. The hardware needs to be able to communicate to the computer to send measurement data and receive the control commands which specify the electrode configuration.

A. Hardware requirements

To properly design the hardware it is necessary to determine what the requirements on the hardware are. These requirements can be determined based on the simulations and small scale experiments. Since it is determined that the voltage change is ratiometric to the applied voltage it is useful to be able to apply higher voltages than strictly required.

In order to keep the experiment safe the voltage difference between an electrode and ground should not be higher than approximately 35 to 40 Volts. Anything above this voltage is considered hazardous in case of a DC voltage. By doing this the maximum difference in potential between the positive and negative electrodes becomes 70 Volts.

From previous experiments it was determined that in the current test setup a worst case current of approximately 32 mA ran between the positive and negative electrode in case 40V was applied. This means that in case of 70 Volts is applied to the electrodes there will be a current of 56 mA. To have some margin the electronics should be able to supply around 100 mA of power to the experiment.

- Each electrode must be able to be the positive supply, the negative supply or a measurement electrode (floating)
- The positive supply electrode must be able to handle 35 Volts.
- The negative supply electrode must be able to handle -35 Volts.
- The measurement electrode must be floating with an impedance as high as possible.
- The output driver must be able to supply 100 mA of current to the test setup.
- The hardware must be able to communicate with the computer via USB to allow easy connectivity and integration into software.

B. Electrodes

The electrodes have to be made of carbon fiber to give the best measurement results. The difficulty with this material is that it cannot be soldered and therefore the copper wire has to be connected in another way. After some experimentation it proved that it was best to wrap a part of the wire with the isolation removed tight around the carbon fiber and then isolate it again with epoxy resin, see figure 8. The electrodes are 6 centimeter long and have a diameter of 7 millimeter, this size was empirically determined to work well and provide enough current in all circumstances.

Fig. 8. Construction of the carbon fiber electrodes

With this construction the resistance between the wire and the electrode is on average 26 ohms with a variance of about 10 ohms indicating that the maximum provided current can be around 830 milliampere at 30 Volts, which is more than sufficient.

C. Mainboard

The hardware of the measurement system has to be interfaced to the computer, since the system had to be scalable it will be divided into modules that each can control a certain number of measurement channels that are connected to the electrodes. The link between the computer and these modules is the mainboard. The mainboard receives the commands from the computer processes them and controls the modules which report their results and get sent back to the computer.

1) Bus network: If each module would have dedicated I/O lines to the microcontroller this would result in the need for a microcontroller with many I/O ports and a more complex control algorithm. This can be avoided by the use of a bus network and addressable modules. It must be possible to address every channel on the system, this can be achieved by putting an address on the bus and having control signals that only affect the operation of a specific module or channel when the address matches. This network is controlled by a microcontroller on the mainboard, all modules are connected in parallel to the bus network. The design of the bus network is shown in figure 9

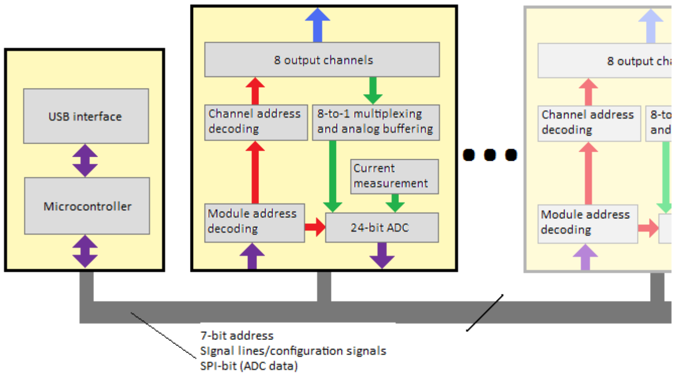

Fig. 9. Bus network for controlling the modules

2) PC interface: To receive control commands and send results to the computer an interface is necessary. Commonly used interfaces are RS232 and USB. The maximum transfer speed that can be achieved over RS232 is fairly low but using the interface is very easy, USB can support much higher speeds but is more complex to use, another advantage that USB has over RS232 is that data is transferred in blocks instead of single bytes. Due to the need of transferring larger amounts of data at high speed while keeping synchronization between the configuration of the electrodes and the measurement data USB is a better choice choice for this system.

3) Microcontroller: To control the modules via the bus network, receive and send data via the USB interface with the computer it is required to have a microcontroller with USB capability. There are many microcontrollers available that support this feature, due to familiarity with this series and availability of a compiler and programmer the choice was made for the PIC18 series of Microchip. More specifically the 18F2550 which supports USB, has sufficient I/O and can run at 40MHz.

D. Switching modules

To allow for a flexible number of electrodes the hardware has to be scalable. This can be achieved by dividing the electronics that drives and measures the electrodes over multiple modules that communicate via a bus network. Each module is able to control a number of electrodes.

1) Switching outputs: One of the main functions of the modules is to switch the outputs to be a positive, negative or floating voltage. This requires components that can handle higher voltages than the standard TTL signal levels. Usually such an output is controlled with a half-h-bridge consisting of an n-channel and p-channel field effect transistor (FET).

Due to the specifications it was chosen to work with a pair of BS170 and BS250 transistors for driving the output for a single electrode, we will call an ‘output stage’. This configuration allows a current of 110 mA and 45 volts. Which is more than adequate considering the specifications given above. In order to control the output transistors with TTL level signals some other low current transistors are required to convert the TTL level signals to the higher voltages required to control the FET’s.

In order to apply the proper voltage levels for the input signals the characteristics of the transistors need to be analyzed, based on the information in the datasheets it is possible to say that:

- The BC857 transistor is in the cutoff region when the base voltage is larger than 4.35 volt. Which causes the FET for the negative voltage to be in the cutoff region.
- The BC857 transistor is in the saturation region when the base-voltage of the transistor is lower than 4.35 Volt. This causes the FET to become conductive and apply V_{neg} to the output.
- The BC847 transistor is in the cutoff region when the base voltage is below the threshold voltage, which is 0.66 volt. This will send the FET for the positive voltage into the cutoff region.
- Because of the high voltage on the collector side we cannot send the BC847 transistor into saturation but in the linear mode it will conduct enough to make the FET for the positive voltage starting to conduct. When the voltage comes above approximately 2 volt it will apply V_{pos} to the output.

This can be summarized to the following conditions for the select signals of the output stages:

Signal	Condition	Effect
S_low	$U_b > 4.35$ ‘high’	The negative voltage is not connected to the output
S_low	$U_b < 4.35$ ‘low’	The negative voltage is connected to the output
S_high	$U_b < 0.66$ ‘low’	The positive voltage is not connected to the output
S_high	$U_b > 2.00$ ‘high’	The positive voltage is connected to the output

From the conditions can be observed that the voltages where the transistors switch are suitable for 5 volt TTL signals. To prevent a short circuit between V_{pos} and V_{neg} the ’select high’ signal is interrupted by a transistor and pulled low by a resistor when the ’select low’ signal is high. By doing this it is never possible that both ’select’ signals are active at the same time and thus preventing a short circuit.

2) Controlling outputs: The test setup will have a limited number of electrodes. Later versions however will have more than hundred electrodes. Therefore modules with eight output stages on one board were made that can be connected to a specifically designed bus network. This allows easy extension of the system and replacement of modules when necessary. It also increases modularity of the electronics and keeps the complexity down. The reason to choose for eight output stages is mainly based on component limitations of the address decoders.

Since there are eight output drivers that each have a select-low and a select-high signal it is required to have two latched 3-to-8 bit address decoders from which the output can also be disabled. In addition to the address decoders there is an 8-to-1 analog multiplexer to select which output is going to be measured. Each of the outputs of the output stages can be selected for measurement and is buffered by an op-amp after the analog switch.

To measure a certain channel the modules are equipped with an 8-to-1 analog switch that supports 36 Volts. The output of this IC is buffered by an (45 Volts) op-amp. This op-amp is configured in a voltage follower configuration to make it possible to use a resistive voltage divider to scale the voltage to a level suitable for the ADC, this cannot be done directly since the voltage divider would influence the potential on the output/electrode.

To use multiple modules on the bus without having dedicated wires for a specific module the modules must be addressable. This addressing is achieved by a 4-bit addressing system consisting of an exclusive-NOR gate and 4-input AND-gate which compare the address on the bus to an address specified by dip-switches on the module.

The output of the AND-gate indicates when the module is selected. This output is used in a NAND-gate and 2-bit D-latch which controls the chip selects for the address decoders for the channels and the chip select for the ADC. The logical schematic of this circuit is shown in figure 10

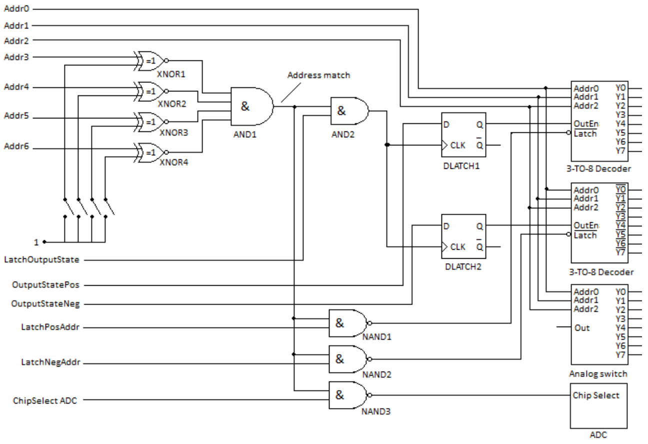

Fig. 10. Logical schematic of the address decoding

An Exclusive-Not-Or-Gates compares the module address with a preset address. If the outputs of all XNOR-gates are a logic one the output of the AND-gate AND1 will also be a logic one. This signal will be referred to as an 'address match' and it is used throughout the controlling circuit for various purposes.

The second AND-gate outputs a logic one when both the 'address match' signal is present and the 'LatchOutputState' input is high. The output of this gate controls the clock signal of both latches. These latches store the input value 'OutStatePos' and 'OutStateNeg' on a rising edge of the clock signal and output these signals on their outputs. This latch is necessary because the 'output enable' inputs from the address decoders are not latched. To reduce the amount of IC's required the second and gate is in reality a 4-input gate where each of the signals is connected to two inputs.

The three NAND-Gates are used to forward the signals to latch the addresses for the address decoders and the chip select signal for the ADC when the address on the bus matches that of the module. NAND-gates are used for this purpose because the latches are transparent when the 'latch signals' are low.

Based on the component datasheets the worst case propagation times for each gate can be calculated which gives a fairly good indication of time the setup of the module takes. These propagation times determine the maximum switching speed. To configure the electrodes some steps have to be performed to configure the module and to make sure no configuration can be reached that may potentially damage the hardware. These steps are:

1) Set module address
2) Disable all the outputs (nothing is either a positive or negative voltage)
3) Set the address for the positive output
4) Set the address for the negative output
5) Set the output states

Since many steps require to set the address which includes the module address it is useful to calculate the time it takes for the 'address match' signal to change. This can be calculated with:

$$t_{addr} = t_{p,XNOR} + t_{p,AND} + t_{RC,XNOR} + t_{RC,AND}$$

Because the switching frequencies will be lower than 1 MHz and the traces on the circuit board will be very short the RC-time can be neglected. In order to have a pessimistic prediction the worst case propagation times will be used. This leads to a 'address match' propagation time of:

$$t_{addr} = t_{p,XNOR} + t_{p,AND}$$
$$= 20 * 10^{-9} + 22 * 10^{-9} = 42 * 10^{-9} = 42ns$$

The next step that will be performed to configure the electrodes is to first disable all outputs on the module. This is done by setting the output values of the latch to the low level. There are some timing requirements for this latch:

The inputs must be stable t_{setup} before the rising edge of the clock and the clock must have a minimum high period of t_W. These values need to be added to the propagation time. We then know that:

$$t_{Latch} = t_{p,LATCH} + t_{setup,LATCH} + t_{W,LATCH}$$
$$= 350 * 10^{-9} + 40 * 10^{-9} + 200 * 10^{-9} = 590ns$$

After disabling the outputs the addresses for both the positive and negative electrodes will be set. Since both outputs are disabled it is not required to wait for the propagation time of these chips since the outputs will only be enabled later, these actions can happen in parallel as long as the timing requirements for the latch are met. This leads to the following formula for setting the positive or negative electrode:

$t_{SetAddr} = t_{Addr} + t_{Setup,ADDR} + t_{W,ADDR}$
$= 42 * 10^{-9} + 50 * 10^{-9} + 50 * 10^{-9} = 142 * 10^{-9} = 142ns$

This time is the same for both the latches for both the positive and negative electrode. When adding these times together we get:

$t_{SetElec} = 2 * t_{Latch} + 2 * t_{SetAddr}$
$= 2*590*10^{-9} + 2*142*10^{-9} + 50*10^{-9} = 1464*10^{-9} = 1.464\mu s$

This equates to a maximum switching frequency of $\frac{1}{1.464*10^{-6}} = 683060 = 683KHz.$

3) Analog to digital conversion: The module also contains an analog path which adapts and provides the voltage to be measured to the analog to digital converter (ADC). Since these ADC's generally allow much lower voltages than those that are used on the electrodes the voltage needs to be scaled. The common way of doing this is with a resistive voltage divider, this will influence the voltage measured on the electrode since it contains one resistor going to ground. To overcome this the signal is buffered by a high voltage op-amp configured as a voltage follower.

Since there are eight channels to be measured a 8-channel analog multiplexer is also required. This multiplexer is placed before the input of the buffer op-amp, the reason for this is to reduce the number of op-amps required and reduce the amount of calibration necessary for the module.

In addition to the voltage measurement the current needs to be measured. This is done with an op-amp that is configured as a non-inverting differential amplifier where inputs are measuring across a resistor that is connected in series. The resistor is connected in series with the positive power supply for the electrodes. By doing this the voltage drop across this resistor can be measured and the current can be calculated using Ohm's law.

To gain some insight in the characteristics one of the inputs of the analog multiplexer was connected to a function generator and the output of the system to an oscilloscope (before the voltage divider). This resulted in a bode-plot which is shown in figure 11.

The bode-plot shows that there is no significant decrease of the amplitude of the signal up to approximately 50 KHz. Despite the fact that the electrodes use a DC voltage it is be possible that when the analog multiplexer switches from channel the voltages change and thus limiting the maximum switching frequency one module to 50 KHz. Since the modules can operate in parallel however having more modules does not reduce the overall speed of the system. The analog-path will allow the system to scan $\frac{50*10^3}{N_{Electrodes}} = \frac{50*10^3}{8} = 6250$ electrode configurations per second.

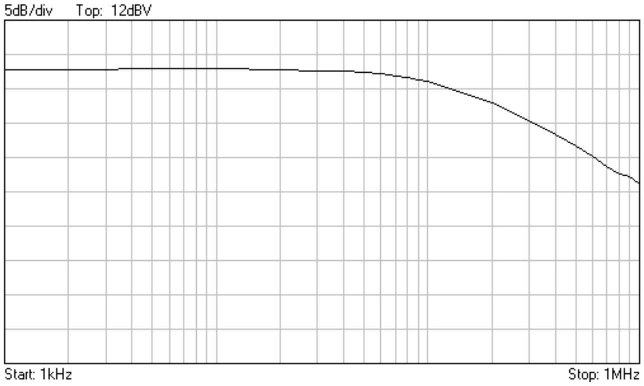

Fig. 11. Bode plot of the analog path, -3 Db point around 50 KHz

Since the analog path can support frequencies up to 50 KHz an analog-to-digital converter (ADC) with a speed of at least 50 KS/s is required. It is also required that the output is of a type that can be connected to a bus network. SPI and I^{2}C are commonly used inter-chip bus networks, the advantage of I^{2}C over SPI is that this type of bus does not require a chip select signal and uses only one data signal instead of two and can be addressed in software. The advantage of SPI is that the overhead of the protocol is much lower and therefore allows much faster communication between the master and slave device. For this reason the choice is made to use SPI instead of I^{2}C.

Since a voltage range of 70 volt has to be measured and the noise level is less than 1 millivolt the minimum resolution for the ADC to not lose any information is 17-bit. Higher is in this case better since it would reduce the need for oversampling to achieve better accuracy.

An ADC that meets these requirements is the Microchip MCP3901 with a sample rate of 64 KS/s and a resolution of 24-bit. In addition to this it has two simultaneously sampling channels that allow measuring the current and voltage at exactly the same time. In addition it is slightly cheaper compared to competitive chips.

E. Power supply

Both the op-amps and the analog switch need positive and negative voltages of ±36 volts to operate. The power supply for the electrode potentials needs to operate at one volt less than the positive supply and for the negative supply one volt more. This is necessary to make sure the buffer op-amp can handle the full scale power. In order to improve the flexibility the power supply is designed with adjustable voltages between 1.25 Volt and 40 Volt and -1.25 and 40 Volt for the negative supply. To make sure the voltage of 40 volts can be reached at the output of the voltage regulators the input voltage must be at least 42 volt. This means that the voltage of the transformer before the rectifier needs to be $\frac{42}{\sqrt{2}} = 29.69$ Volt, therefore a 30 volt transformer is chosen. The minimum current is 100 milliampere, in order to have margin the power supply can provide 150 milliampere.

Final versions of this system might have to work in remote locations where an infinite power supply is not always available, therefore it is important to know what the power consumption of the system is. From the small scale experiments it is known that the maximum current running between the electrodes is approximately 56 milliampere. The logic part of the system draws less than 50 milliampere and the analog path draws less than one milliampere. Which means that the total current drawn is less than 110 milliampere.

VI. SOFTWARE DESIGN

The hardware of the system cannot perform tasks without having some software in the microcontroller, the firmware, controlling it. The firmware performs all low level tasks such as sending the addresses to the modules, reading the analog values and sending these to the computer via the USB connection. In turn this firmware is controlled by an application running on a computer system that will configure the firmware to use a certain electrode configuration and use the returned data to reconstruct a graphical interpretation of the cross sectional resistance.

A. Data acquisition

The results that are captured by the analog to digital converter need to be transferred to the computer. In order to be able to do this the microcontroller needs to control the electrode configuration and place the data in a certain format such that it can be sent via the USB interface. The computer will receive these values and convert them to potentials and currents and use these values to reconstruct a cross-section of the resistance.

1) Firmware: The commands that are sent from the computer to the measurement system via USB have to be converted into specific actions that control the modules via the dedicated bus network. The USB is configured to register itself as a Human Interface Device (HID) that allows speeds up to 1.2 megabit per second and frame sizes up to 64 bytes. and The firmware can perform several tasks which are:

- Receive new electrode configuration: this will cause the microcontroller to reconfigure the positive and negative electrode of the system.
- Receive measurement command: the potential on the specified electrode will be measured and sent back to the computer.

To set a new configuration the firmware first switches all electrodes off, then sets the new addresses and only after that the electrodes are again enabled. This takes a small amount of extra time but prevents configurations that have multiple positive or negative electrodes which can result in a too high load on the power supply, it also prevents that momentarily the same electrode is configured to be both positive and negative. Although the electronics are protected against this situation this acts as a second layer of protection.

In each message that is sent back the measurement configuration is also included, this is used to make sure the software on the computer will use the correct message with measurements for the right electrode configuration, otherwise a delayed message might be related to another configuration and can lead to wrong results.

2) PC software: The highest level of control originates at the computer that communicates via the USB interface with the firmware on the hardware. It can send configuration and measurement commands. After sending a measurement message the returned data will be received and converted to a voltage and a current from two's-complement format. Three measurements are made and averaged to the value for one electrode.

These results are stored in an array and a running average is computed for each electrode, this average will be stored from measurements over a longer time and new measurements will be compared against this average to calculate the voltage difference against the long term average. These delta values are stored in an array containing all measurements for a certain electrode configuration and are later used for the image reconstruction.

The software scans all required electrode combinations, that are specified in a list, and scans per configuration all electrodes. This requires one 'configuration message' for each step and a 'measurement message'.

3) Optimizations data acquisition: During testing the system for functionality it was noticed that the communication speed on the USB interface did not reach the expected communication speed. After some investigation it the cause for this was found in the windows USB library for HID devices. It can only send and receive a message once every 10 milliseconds. Because of the large number of measurement messages that is sent the system becomes slower than expected. They are however required to keep synchronization and cannot be removed without making the system less reliable and predictable. The initial version uses $Averaging * N_{Electrodes} * N_{configurations} = 96 * N_{configurations}$ messages per complete measurement of the system.

The first optimization made was to do the three measurements on the microcontroller and send them as one block of data to the computer at once. This reduced the amount of measuring by the number of averaged values. The number of messages sent via USB is now $32 * N_{configurations}$ messages.

The second optimization was to send the three averaging values for four electrodes at one time which reduced the amount of messages sent to $8 * N_{configurations}$ per full measurement, which is again an improvement of a factor of four. The number of electrodes sent at once cannot be further increased due to the 64 byte limit.

The last optimization is in the order the electrodes are read, until now the electrodes are scanned from 0 to 32 which means that for every read the analog multiplexer has to switch which takes $10\mu s$. Since the addresses of the multiplexers are not clocked they will switch in parallel for each module. Since each module contains eight electrodes it is more efficient to read the electrodes in the order of 0,8,16,24 followed by 1,9,17,25 and so on. This reduces the amount of necessary switches by four.

B. Image reconstruction

The data received by the data acquisition part of the software is preprocessed to be used in the image algorithms, the delta values for both the potentials for each electrode and the current values as calculated and stored in an array. These values have to be processed by an image reconstruction algorithm to create the two dimensional graphical representation of the resistance changes. There are two reconstructions created that are later merged to form the final result, one potential based reconstruction and another based on the current changes.

1) Potential based reconstruction: Based on the delta values of the voltage an image has to be reconstructed that shows the cross-section of the resistance. This means that the electric field has to be reconstructed from values that are only measured on the edge of the electric field. This reconstruction can be done with the Laplace formula which determines the value for each unknown field by taking the average of the fields around it. This can be computed by generating a set of linear equations that can be solved with Gauss-Jordan elimination.

The generation of the set of equations followed by the Gauss-Jordan elimination to solve will be done for each electrode configuration which will result in an image of the disturbance in the electric field for just that measurement only. These resulting matrices are added together to merge the sub-results into the final matrix. This matrix will be normalized and drawn in a graph, the dataflow is shown in figure 12.

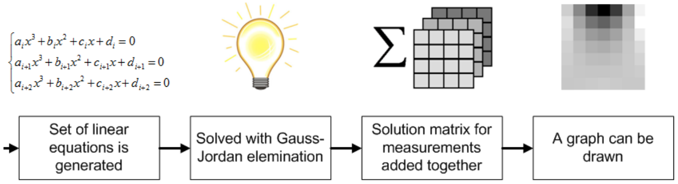

Fig. 12. Steps for calculating the voltage based reconstruction

The image reconstruction is started when the measurement is completed and the 'running calibration' is valid. This calibration becomes valid after doing a minimum number of measurements to get initial values for the averaging.

This algorithm uses per electrode configuration $n^3 + n^2$ divisions, n^3 multiplications and n^3 additions, where n is for an $n \times n$ matrix. Which is a total of $3n^3 + n^2$ operations that are performed per electrode configuration. After all single matrices are solved they are added together which takes n^2 multiplications making the total of $N_{configurations} * (3n^3 + n^2) + 4n$ operations performed.

Since calculating the average of some sets of values and adding these averages together is the same as adding the values together and then calculating the average (for sets of equal size) the algorithm could be optimized to use $3n^3+n^2+4*N_{configurations}*n$ which means that the number of calculations now scales lineair with a very slight increase in computation time when more electrode configurations are processed. In essence this means that extra electrode configurations and therefore improved accuracy can be added with almost adding no additional computation time. The dataflow of the algorithm after optimization is shown in figure 13

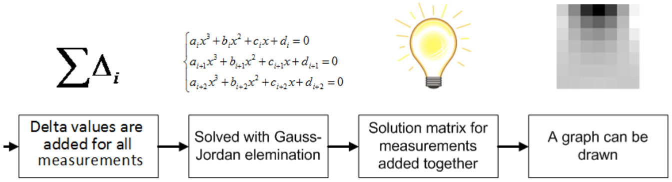

Fig. 13. Steps for calculating the optimized voltage based reconstruction

2) Current based reconstruction: The potential based reconstruction gives good results when the object is not to close to the middle of the tank, this is due to the averaging effect resulting from the Laplace equation, this effect can also be observed in figure 3 where the electric field has a very small gradient in the middle. To overcome this problem a current measurement is performed in addition to the voltage measurements. When the object with the lower resistance is in the middle the current change from the activated electrodes will be higher for electrodes in the middle of the tank compared to those in the middle of the tank.

The current reconstruction determines the position of the activated electrodes and determines the path between then as well as the length of this path. Since the voltage at both electrodes and the current is known the resistance between the electrodes can be calculated. This resistance is normalized by the length of the path and added to a two-dimensional matrices at all fields that are crossed by the path between the electrodes, this is shown in figure 14. The normalized resistance for each field is $R_n = \frac{(U_{pos} - U_{neg}/I)}{\sqrt{(X_{pos}-X_{neg})^2+(Y_{pos}-Y_{neg})^2}}$ where U is the potential, I is he current and X and Y are the electrode position.

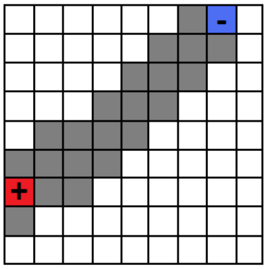

Fig. 14. Determining the path between the positive and negative electrode

The path is determined for each electrode configuration and all paths are averaged. This leads to a second matrix with another reconstruction that takes into account current changes and is not depending on changes in potentials. With this algorithm combined with the potential based reconstruction there is also the possibility to see objects that are in the middle of the tank.

The computational complexity is depending on the scan pattern, which electrode configurations are measured, but when worst case is assumed there are $9 * n$ additions and $3 * n$ divisions, this results in $12 * n$ operations. The total number of operations required to calculate the current based resistance map is $12 * N_{configurations} * n$ which implies linear scaling with both the number of electrode configurations and size of the matrix.

3) Combining the results: The results of the two different algorithms both have their advantages, the potential based algorithm gives higher accuracy and the current based algorithm is able to better reconstruct situations where the object is in the middle of the tank. By combining these results a good tradeoff can be achieved between them. In order to do this the results of both algorithms are normalized and added together where the influence of each of the algorithms is weighted to allow adjustment of the result.

VII. EXPERIMENTAL RESULTS

In order to verify the results of the simulations some tests have to be performed with the developed system. For these tests there are 32 carbon fiber electrodes placed in a small tank of 40 by 40 centimeters with a layer of approximately 10 centimeters of water. The electrodes are connected to the hardware which in turn is connected to the computer via the USB interface. The computer software is configured to scan all electrodes in horizontal and vertical direction as well as various diagonal situations to improve the results of the measurement. For these experiments a piece of fish with a diameter of two centimeters has been placed vertically in the tank.

A. Image reconstruction

Reconstruction of the images showing the resistance levels of the water in between the electric field is one of the most important features of the application. In order to confirm the simulation results a real world measurement is performed with the conditions and setup as described before. The results were gathered and loaded in the reconstruction algorithm. Both potential and current reconstruction were applied for the reconstruction which gives the result shown in figure 15.

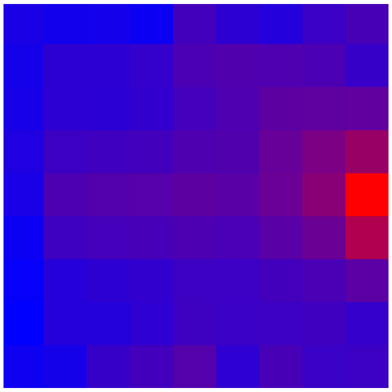

Fig. 15. 32-electrode reconstruction based on actual measurements

Measurements on the reconstruction algorithm show that almost all processing time, more than 99% is consumed by the potential reconstruction algorithm. This indicates that this algorithm should be optimized further, possibly by using a graphics processor. In addition to the experiment described above an experiment with two objects has been performed to investigate whether multiple detection is possible, the results seem to support this indicating that the occlusion problem that occurs with optical and acoustical systems can be avoided.

B. Resolution

One of the important factors for later algorithms to recognize the fish is the resolution of the reconstructed images which depends on the number of electrodes. In order to be able to see more detail the measurements can also be interpolated. In order to do this cubic interpolation is used which calculates the potentials of the electric field in between the actually measured potentials of the electrodes. Figure 16a shows the native reconstruction for a measurement using 8 electrodes, 16b shows the interpolated version. If this result is compared to figure 15 it can be observed that the 8-electrode interpolated measurement comes close to the real 32-electrode measurement but does not show as much detail. In fact it can be observed that the interpolated version of the 8-electrode setup, which has three electrodes per side, is three times lower compared to the real 32-electrode setup which has nine electrodes per side. From this it can be concluded that the size of the object that will be visible is equal to the distance between the electrodes.

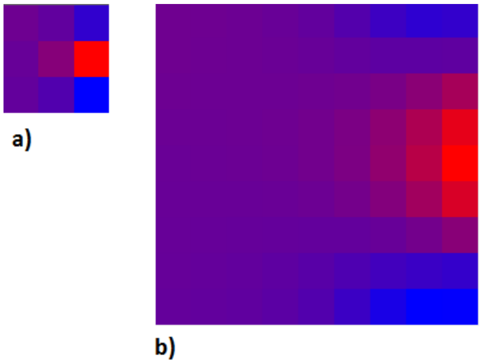

Fig. 16. 'Native' 8-electrode reconstruction and interpolated reconstruction

To accurately see the shape of an object in the reconstructed image the resolution and therefore the number of electrodes most likely needs to be increased further. The modular design of the system will easily allow this to up to 128 electrodes. This can be extended to much higher numbers if necessary with minimal changes to the hardware and software.

C. Switching speed

During one of the experiments some unexpected results appeared, during some measurements it appeared that in between two electrodes there was an electrode that could have a higher voltage than both of the other electrodes. Since the electric field is either increasing or decreasing gradually these measurements were unexpected. After some investigation it proved that the cause was in the fact that the polarity of the electric field was reversed often. This leads to a remaining charge in the water which cannot be dissipated quick enough by the electrodes to prevent it to show up in the new measurement. This problem was solved by modifying the order the different electrode configurations were measured in such a way that the polarity of the electric field changes as little as possible. After doing this the effect was not observed again.

VIII. PRODUCTION COST

To compete with other systems it is important that the production cost is low. The price for components and circuit boards decreases rapidly when the ordered amount goes up but in order to give a pessimistic estimation the component and circuit board cost are calculated for a single measurement system.

The total cost for all components for one measurement module is slightly over 50 euro, the circuit board contains 222 components that need to be placed which costs approximately 1.9 cents per component. A circuit board of the correct proportions costs 17.70 euro making the total cost for one measurement module 72 euros'.

The mainboard costs approximately 7.50 euro and 3.50 euro in components for each module that needs to be connected. Therefore for a system with N modules costs $7.50 + 17.70 + N * (3.5 + 72)$ euro to produce, for the test setup with 4 modules this would be 327.20 euro. This cost will go down quickly when multiple systems will be produced at once.

In addition a computer is required to process the data. Which adds approximately 800 euro to the cost of the system. The computer system can later be replaced by a dedicated circuit board with an FPGA and possibly a graphics processor to reduce cost and increase speed. Based on the current price it is expected that the system can compete with camera and sonar based systems with the added advantage of the capability to be able to detect fish in turbid waters.

IX. FUTURE WORK

The current design leaves space for further research and improvements as the current prototype can be extended and optimized. The algorithm that is currently used can be adapted to run on a graphics processor which should make it much faster. This is possible due to the fact that many of the matrix operations can be done largely independent from each other. In addition to this the algorithm can be extended to create side views of the objects visible in the reconstructed images which allows for a vision recognition system to detect the shape of the object and classify the object as a certain species of fish or another object. This classification will be performed using pattern recognition.

The computer that processes the data can be changed by an FPGA that computes together with a graphics processor the reconstruction algorithm and directly controls the modules, eliminating the need for the USB interface, which should again improve the speed by a large extent. Based on these improvements some field experiments have to be performed to confirm that the measurement speed is fast enough to yield valid results.

X. CONCLUSION

This paper describes a system for creating a two-dimensional reconstruction of the resistance of the cross section of a body of water. Based on a description of the concept an extensive simulation using both two-dimensional and three-dimensional models was performed which showed feasibility of the concept. Based on these simulations functional requirements were specified which lead to development of dedicated hardware and software which allowed for a real world experimental setup.

The results for the real world experiments show very much the same result as the results for the simulations which validates the simulations and shows the feasibility of a system creating reconstructions of resistance in water. These reconstructions can be used as the input for algorithms that recognize actual species of fish. In addition the measurements show that the smallest size of the object that can be detected depends linearly on the amount of electrodes per side of the measurement setup which means that the system can easily be scaled to the requirements of a specific location.

Based on the current prototype there are still optimizations and extensions possible, these include for example the addition of an FPGA for direct communication with the modules and a graphics processor for much faster computation of the reconstruction algorithm.

If the new method is compared to existing methods the resolution is still lower but this can be solved by increasing the number of electrodes and with that increasing the resolution, a large advantage of the resistive imaging is the ability work in water that is too turbid for camera's and contains to many particles in suspension for sonar. In addition the cost of the new system is many times lower than the sonar based method and will be roughly equal to a camera based system. Which makes this method a good alternative in situations where the use of existing methods is limited by the environmental conditions.

Based on the results a patent has been filed under number 2006056.

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