World Robot Olympiad – Future Innovators category (Senior) 2023

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Team name: **Swarm Intelligence**

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Our Team

The members of our team are Bence Kakuszi, Olivér Forgó and Katalin Hanga Tóth. We have been a team since January 2021 and participated in a project together in the last WRO season. The division of labor within the team is natural. Oliver's strength is electronics, so he enchants ARDUINOs and designs circuits. Hanga is good at LEGO programming, so he develops graphics programs. Bence understands everything, so he helps others in addition to building.
In addition to LEGO projects, we love physics, chemistry, math, and programming, but only the more creative version when it comes to thinking about problems.
Anyway, besides programming, maybe pancakes, which is a common hobby.

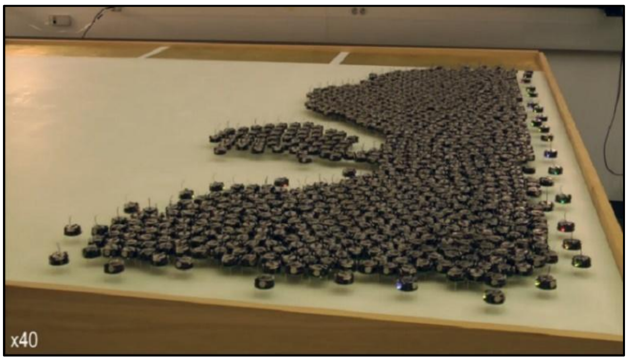
Introduction

IT communication in the XXI. is a defining area of information technology. By this we primarily mean the relationship between people, and digital technology appears as a means of communication.
With the development of artificial intelligence research, the role of humans is often taken over by machines. One branch of research is swarm intelligence, which models biological systems using examples from the animal world and creates a new platform for communication.
Among the biological life forms operating in swarms are ants and bees, which show a significant difference in communication compared to human IT technology communication.

https://zeeshanusmani.com/wp-content/uploads/2019/11/Swarm.jpeg
https://www.pestwiki.com/wp-content/uploads/2018/04/shutterstock_420364003.jpg
https://ucanr.edu/blogs/bugsquad/blogfiles/9982.jpg

Several land and aerial (drone) implementation models have already been created in this field of science, primarily for reconnaissance purposes.



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https://sites.breakingmedia.com/uploads/sites/3/2022/03/220309_DVIDS_drone_swarm_5356116-scaled-e1646850673463.jpg

We have not yet found an example of the implementation of underwater robot swarms.

The impact of environmental changes also has a great impact on marine life. The continuous monitoring of the composition of natural waters and the creation of a big-data database based on the collected data can predict changes whose timely detection can provide a chance for intervention. For example, the dissolved oxygen content of natural waters is a prerequisite for underwater life. Since the solubility of oxygen in water decreases with increasing temperature, an increase in the temperature of the seas (as a result of global warming) can have serious consequences. Several scientific articles and analyzes have been prepared in this regard. For example, about the death of crabs in the Baltic Sea, or the dead ecosystem of the regions of the Black Sea below 200 m.
https://www.eea.europa.eu/hu/articles/hal-a-vizben-tengerek-az-eghajlatvaltozas-tukreben
https://pubmed.ncbi.nlm.nih.gov/18703733/

Swarms of submarine robots can help collect data quickly and easily.

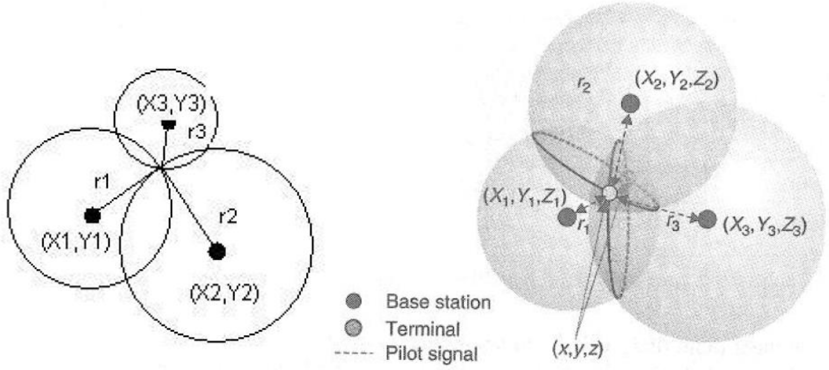
The biggest challenge is underwater communication. Radio waves do not work underwater. Several ongoing researches are still trying to find a solution for fast communication. These primarily use light (laser) as a transmission medium.
https://raketa.hu/wifi-utan-itt-az-aqua-fi
https://www.okosipar.hu/viz-alatt-is-mukodnek-es-kommunikalnak-a-dronok/
https://www.semanticscholar.org/paper/A-meta-analysis-of-the-status-of-ICES-fish-stocks-Sparholt-Bertelsen

The disadvantage of voice-based communication is that the amount of data that can be transferred is small, so even the transmission of an image remains below the transmission speed of an analog modem. If we use swarms of robots for research, there is no need to transfer a large amount of data, because the robot units can store measurement data and images. For data collection with scientific accuracy, the position of the individuals of the swarm is necessary so that the location of the measurement data can be determined. Positioning requires the transmission of a relatively small number of signals, which can already function with sound-based communication.

Whales do not normally form large groups, but again modeling the biological system can be useful. The meaning of the sounds made by whales has not yet been scientifically deciphered, but the technique can be used. The sound of the blue whale, with a volume of up to 190 decibels, can be heard in the water at a distance of hundreds of kilometers.
https://hu.better-pets.net/12016281-how-do-whales-communicate

Another sound-based method can be sonar technology, which was already used in the detection of submarines during the II. World War. According to our concept, the individuals of the robot swarm collecting data must know their own position and store it together with the measurement data. The sonar technique only makes this possible if the geometry of the underwater area to be explored is known, so the position has a point of reference. To determine the location of the underwater robots, we use three sound-emitting buoys which calculate the distances measured from the buoys using the method of mathematical triangulation. The coordinates are then stored, and the depth is stored as the fourth coordinate. These are relative coordinates.

Once on the surface, the relative coordinates can be converted into absolute coordinates (GPS coordinates), if the location of the buoys is known.



$$r_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2}$$

http://pallergabor.uw.hu/hu/univ/loc/1-basicloc.pdf

Our concept is that swarms of small submarines operating independently but working in swarms carry out reconnaissance of the terrain. They use different digital sensors to measure the composition of the water (PH, dissolved oxygen, mineral salinity, temperature, etc.) or map the underwater area by taking photographs (sonar images). The measurement is continuous. As data recording, relative coordinates and measured values are stored in a database. When the data rises to the surface, it is included in a big data set. Swarms of robots are able to map even a significantly large area much more efficiently and quickly and keep it under constant surveillance.

With their help, even the Loch Ness monster can be found. 😊

Next, we present the theoretical background of the research and the practical details of the model.

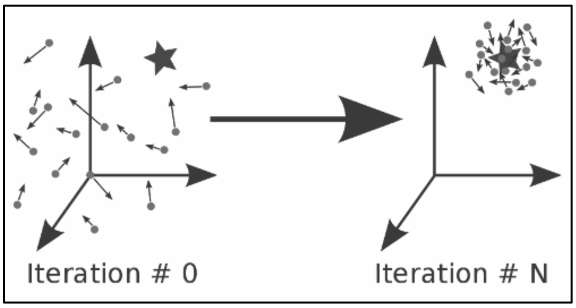
SWARM INTELLIGENCE

In the last decades the improvement of informatics and robotics made it possible to study different algorithms inspired from nature. A great example of this is the phenomenon of swarm intelligence discovered in ant and bee colonies.

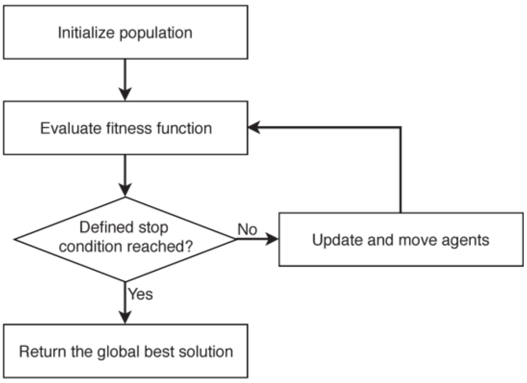
Swarm intelligence refers to the collective behavior of a system whether it is natural or artificial. Such a system consists of simple agents interacting with their environment. The individuals pursue relatively easy tasks and follow simple rules without a direct superior giving them orders to follow. The interactions of these agents lead to the emergence of a global intelligence unknown to the agents. Every individual is responsible for their own task to solve the problem regardless of what others are doing. Systems based on swarm intelligence adhere to a couple of regulations, called swarm principles.

- Autonomy:
  Every agent must self-coordinate and function as an autonomous master.
- Awareness:
  Each particle has to be aware of its surroundings and abilities.
- Solidarity:
  When the given task is completed the agents must commence to look for a new task.
- Expandability:
  The system must permit dynamic expansion where members are seamlessly aggregated.
- Resiliency:
  When agents are removed the system must be self-healing.

The application of swarm principles to robots called swarm robotics. This field of robotics can be used to create maps just like social insects contribute to find food and water. Each robot explores an area independently. The information gathered together from all of the robots make it possible to create the map of the whole given area. Swarm intelligence algorithms can be easily used to find specific targets in a region. Similarly to ants, every agent searches independently and when one element of the system finds the target, its location becomes a collective knowledge, therefore all of the individuals are able to find the target.



Another approach towards swarm intelligence is using its advantages in artificial intelligence. Instead of physically searching for something, the algorithms can be implemented in order to find the best optimized solution to a problem. Every individual's task is to come up with a solution on their own. Then a combination of all of the different responses can create a better solution than any of the independent participants'.



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G.Beni, J. Wang, Swarm Intelligence in Cellular Robotic Systems, Proceed. NATO Advanced Workshop on Robots and Biological Systems, Tuscany, Italy, 1989.

Clough, B.: UAV Swarming? So What are Those Swarms, What are the Implications, and How Do We Handle Them? Proceedings of the AUVSI Unmanned Systems Symposium, , Orlando, FL., July 2002.

Mini Submarines

Unmanned underwater vehicles (UUV) are used for various reasons, like searching the seas or mapping the seafloor. They can withstand high pressure, and thus can operate underwater safely. There are also remotely controlled robots which carry out similar tasks. Some underwater robots can reach up to a few thousand meters of depth, even though our project doesn't require that much, these depths are limited by their ability to withstand high pressure.

There are existing experiments for using swarm intelligence underwater, however they are not used in practise like we intend. Researchers at Harvard University made a fish like robot that moves in a group and can perform different tasks. These fish are quite small and operate in a close proximity to each other.

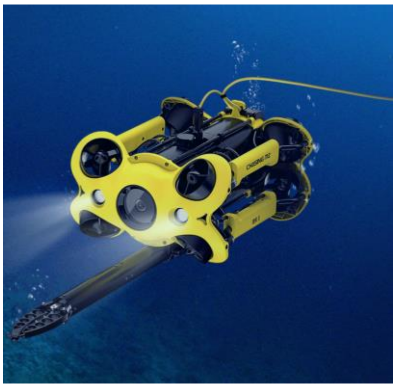
Our goal is to create a system of individual underwater robots that work together using swarm intelligence and solve different problems. According to the internet this hasn't been done in practice by anyone.

https://www.youtube.com/watch?v=1pflbeDRkUs&ab_channel=HarvardJohnA.PaulsonSchoolofEngineeringandAppliedSciences
https://wyss.harvard.edu/news/robotic-swarm-swims-like-a-school-of-fish/
https://en.wikipedia.org/wiki/Autonomous_underwater_vehicle
https://www.oceaneering.com/space-systems/robotics-and-automation/

The typical diving depth of commercially available underwater drones is 100 m.

Power supply via battery, approx. 2-6 hours. In many cases, these drones serve hobby purposes and are equipped with a camera that can be used to take underwater pictures.

Their industrial application is only possible to a limited extent, they can be controlled individually, they do not have an artificial intelligence algorithm and they cannot communicate with each other. Drones that are also used in industry (e.g. suitable for inspecting docks and ship hulls) maintain contact with the surface operator with a flexible cable bundle that supports communication transmission. They do not work independently and cannot work in swarms.



https://www.uavfordrone.com/product/chasing-m2-professional-industrial-underwater-drone-robot-rov/
https://s13emagst.akamaized.net/products/39764/39763189/

Our project requires submarines to be equipped with digital data collection sensors. With a processor that ensures intelligent behavior and software that helps independent operation and orientation, as well as a controller capable of running them. An additional electronic supplement is required for communication.

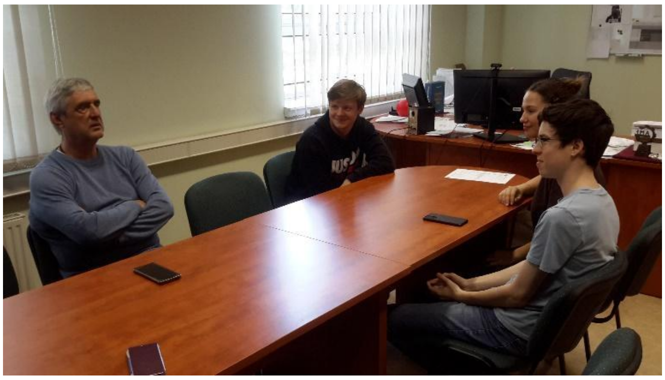
UNDERWATER COMMUNICATION BETWEEN ROBOTS

Underwater communication is much more complicated than the traditional communication based on radio waves. Radio waves cannot be reached underwater. The signal transmission speed is very slow. Based on the ideas expressed in the introduction, we examined voice-based communication in our project. In our model based on the principles of swarm intelligence, the robot submarines must know their relative position in relation to the three buoys placed on the surface of the water when collecting measurement data. By storing these relative coordinates and supplementing them with the 4th coordinate, the depth, the position can be coded back on the surface. For this, the exact coordinates of the three buoys must be known, which can be determined using GPS coordinates on the surface.

In the course of the research, we contacted external experts who helped us identify the problems and pointed us in the direction of possible solutions.
On the subject of swarm intelligence, Dr. Attila Pásztor, head teacher of the Technical Faculty of János Neumann University, was our consultant. (His professional publications are also included in the referenced literature of the swarm intelligence chapter.)

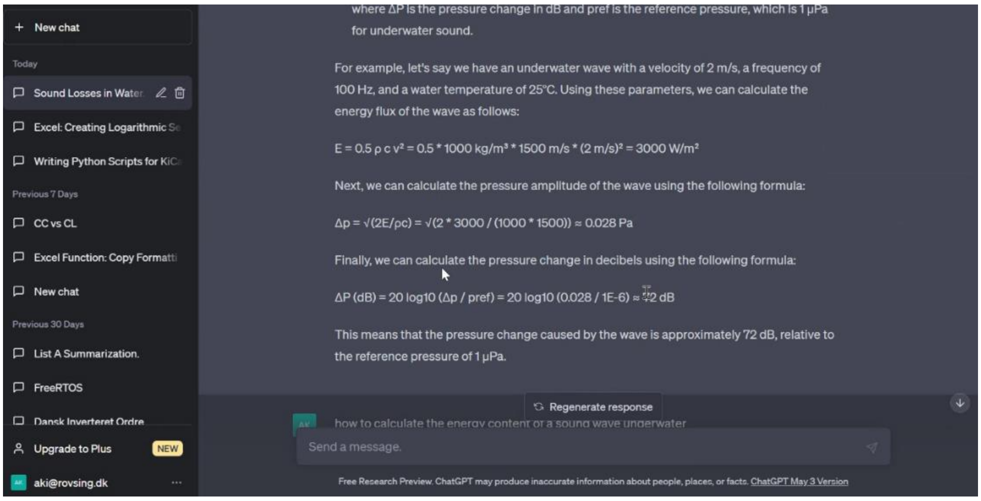
Ádám Kiss (Hardware Engineer) helped with the topic of underwater sound detection and transmission. (He is currently working on the software and hardware development of the Satellite Test System at Rovsing A/S in Copenhagen. Previously, he developed the wireless sound transmission systems of the Danish company Kombo Audio.)

We used the help of GPT-4 several times for the details of the calculations. (In each case, we followed the tips given by OpenAI back to the source and they proved to be reliable.)



Consultation at the university (Dr. Attila Pásztor, Hungary, Kecskemét)

Online consultation (Ádám Kiss, Denmark, Copenhagen)



Consultation with GPT-4 (on the Internet)

In the first step, we determined (estimated) the measurable propagation speed of sound in water. For this, we used a partially empirical formula.

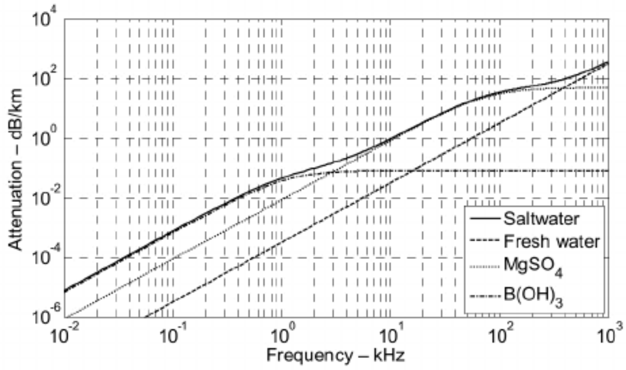
$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016D$$

The meaning of the letters in the formula and the values used:

T – Temperature (degC) □ 10
S – Salinity (ppt) □ 35
D – Depth (m) □ 100
c – Speed of sound in water (m/s)

The obtained value: 1491.59 m/s (corresponds to the literature value.)

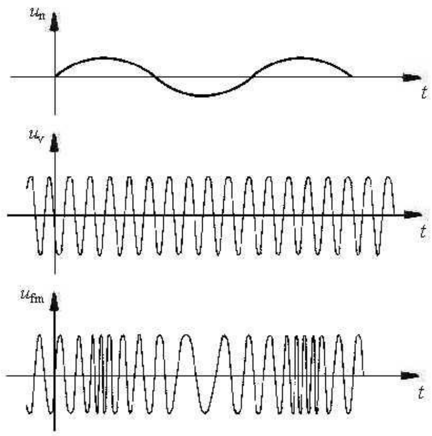
To determine the position of the robot, we place three sound-emitting buoys on the surface of the water, which continuously emit sounds of different frequencies. Robots detect these sounds. Since the three buoys emit at different frequencies, they can be distinguished, so the distance of the robot from the buoys can be calculated separately.
The robot must know its current distance from all three buoys in order to store the location of the sampling. Determining the radiation frequency of the buoys is important. The absorption loss of the medium (water) increases with increasing frequency.



https://www.researchgate.net/figure/Acoustic-absorption-dB-km-for-fresh-water-and-saltwater-plotted-as-a-function-of_fig8_256453572

At the lower limit of the human hearing range (20 Hz-20 kHz), the loss is practically negligible. Whales also communicate on this frequency. (This is why their voice can spread over hundreds of kilometers.)

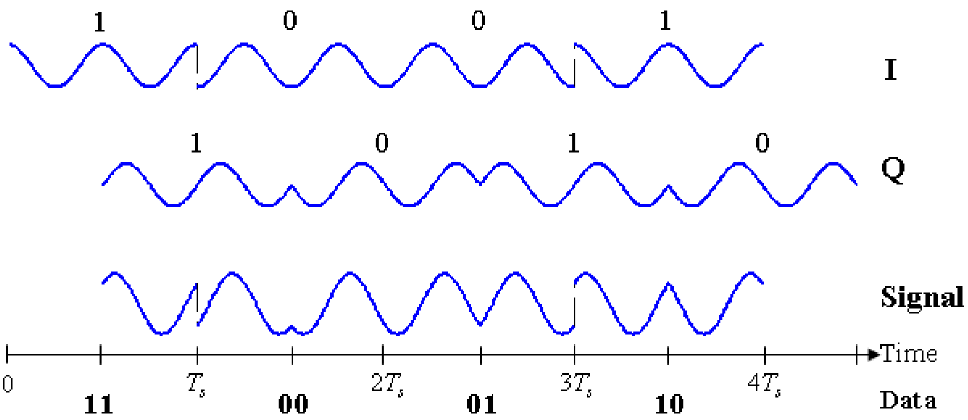
A synchronized clock signal is required to determine the position of the buoys. By detecting the sound emitted by the buoy, the robot can determine the distance from the elapsed time (knowing the speed of propagation). It is possible to synchronize the clocks of the buoys and the robots, but since the buoy emits a periodically repeated sound, the robot needs to know when the sound was emitted (relative to the detection). Therefore, e.g. with frequency modulation, the buoy puts the time signal on the emitted sound. Upon detecting the sound, the robot can calculate the deviation from the base frequency based on the given frequency, so the time of emission will be known.



Frequency modulation (FM)

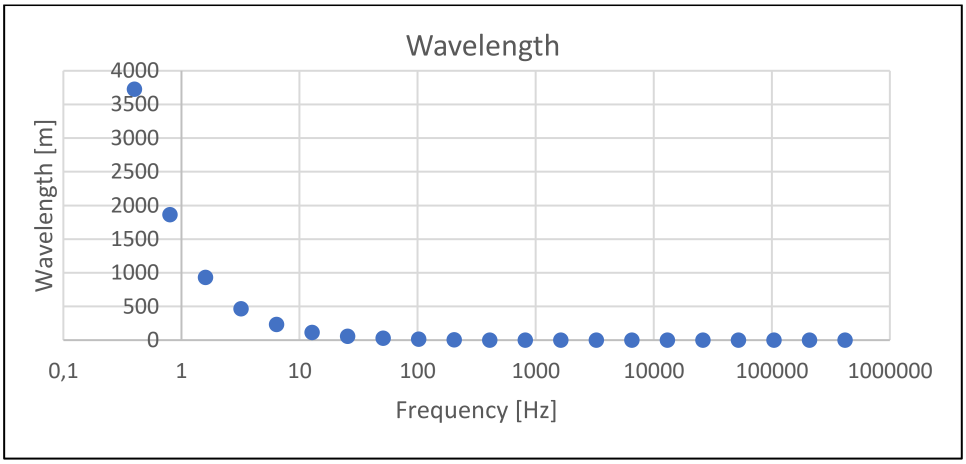
https://wiki.ham.hu/index.php?title=F%C3%A1jl:FM1.jpg

Coding of the time signal to the carrier wave is also possible using the Phase Shift Key technique. (also used with GPS). In practice, we can also use a binary (or even 4-digit) code by sending a sine wave signal with phase rotation.



https://upload.wikimedia.org/wikipedia/commons/4/43/OQPSK_timing_diagram.png

We examined the change in wavelength as a function of frequency. Excel-based graph calculated by the team:



The accuracy of distance determination increases at higher frequencies, as the wavelength is significantly reduced. However, the absorption loss also increases.

According to our estimate, the buoys' radiation frequency should be around 10-20 Hz. (See whales.)

We calculated the ratio of the energy entering the microphone at some frequencies. For this, we used the fact that sound propagates along a spherical surface. The surface area of the microphone was chosen to be 0.0004 m^2.

Radius (m)	Surface (m2)	The ratio of the energy entering the microphone
0,1	0,125663706	0,003183099
0,2	0,502654825	0,000795775
0,4	2,010619298	0,000198944
0,8	8,042477193	4,97359E-05
1,6	32,16990877	1,2434E-05
3,2	128,6796351	3,10849E-06
6,4	514,7185404	7,77124E-07
12,8	2058,874161	1,94281E-07
25,6	8235,496646	4,85702E-08
51,2	32941,98658	1,21426E-08
102,4	131767,9463	3,03564E-09
204,8	527071,7853	7,5891E-10

At a radius of around 100 m, the amount of energy reaching the microphone is quite small, but it can be solved technologically.

Based on a source we found on the communication of whales, we calculated that if we emit a sound at 190 decibels (the whale does approximately this), then what will be the pressure difference (wave average) generated by the sound. The relation we used is:

$$L = 20 \cdot log_{10}\left(\frac{p}{pref}\right) ⍰ p = pref \cdot 10^{\frac{L}{20}}$$

pref – reference value for 1 decibel: 1E-07

L – 190 decibels

The sound pressure value for the whale's wave average: 316.228 Pa (Pressure difference on the wave front.)

Our calculations proved that, in principle, underwater communication is feasible.

However, several factors were not taken into account. These are important and can be decisive.

Disturbing effects:

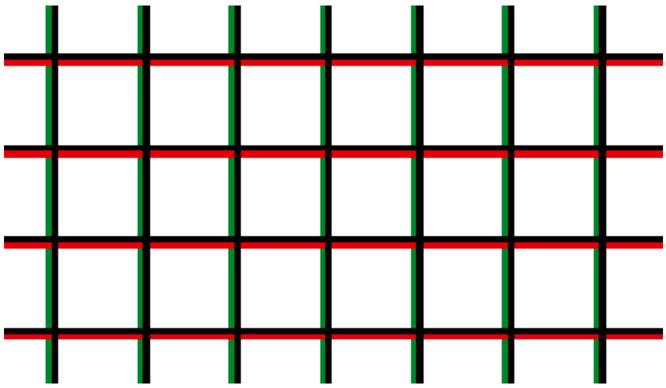
- Sound propagation depends on the temperature and salinity of the water. (In the case of a large water mass, it does not change quickly.)
- Signals reflected from the bottom can cause interference. (Can be eliminated by software. E.g.: we use the earliest incoming signal as a basis.)
- Doppler effect (This can be a serious problem. It has a smaller effect with shorter wavelengths.)
- Background noise (E.g.: boat engine. The strength of the relevant signal must be at least twice the value of the background noise in order to be able to detect it stably.)
- Flows

THE MODEL

We do not use underwater robots in our developed model. The calculations of the previous chapters support that all of this would also work underwater.

In the model, we created a robot swarm consisting of four individuals that explore an area. In theory, they examine some component that can be measured in water (e.g. oxygen dissolved in water). All of this was modeled with tiles of different colors placed on the test surface. The robots travel independently of each other in their own area. Each robot runs the same program. As they move, they monitor the color of the surface with their color sensor.

Their relative position is not determined by triangulation, but with the help of colored bands placed on the surface to be explored.



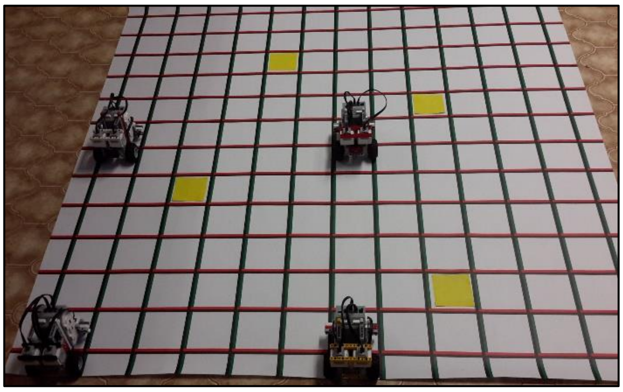
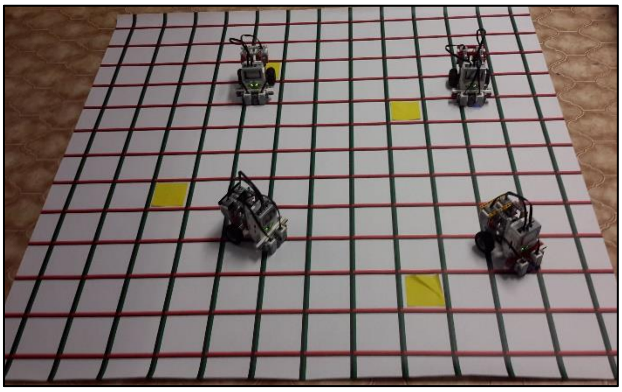
We used three colors. The scanned colors and their scanning order determine the robot's direction of movement.

red-black → north
black-red → south
green-black → east
black-green → west

Based on this, the robot can determine a relative coordinate compared to its starting position. The movement is performed by orthogonal movement.

One of the two color sensors placed on the robot monitors coordinate crossings, while the other monitors the color of the area to be explored (as if measuring the composition of water with a sensor).

A total of four robots walk the track, starting from different positions.

The measured values are continuously sent via Bluetooth to a server (fifth EV3 brick) which communicates with an ARDUINO microcontroller. The server knows the absolute starting position of the robots, so it can create a map of the entire area based on the received relative values. ARDUINO is responsible for displaying the data, which is displayed graphically on a screen in real time.

In the planned project, due to the slowness of underwater communication, the data will only be transferred to the server (and the database) at the end of the walk. For the sake of visuals, the team decided on realtime display.

With the model, we wanted to model field reconnaissance based on swarm intelligence, as well as the possible use of available data from the mapped area. The graphic display gives a much more comprehensive picture of the conditions of the area.

As a further development, the robots can comb the problematic area in more detail, since the coordinates are available, so they can gather in the area in question and perform new measurements after receiving them from the server.

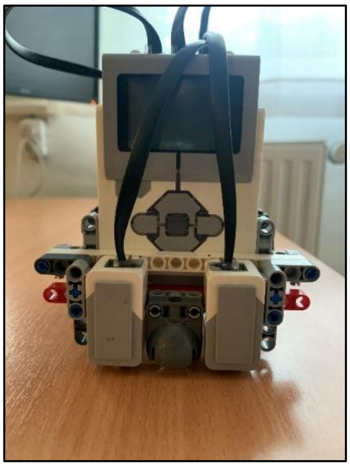
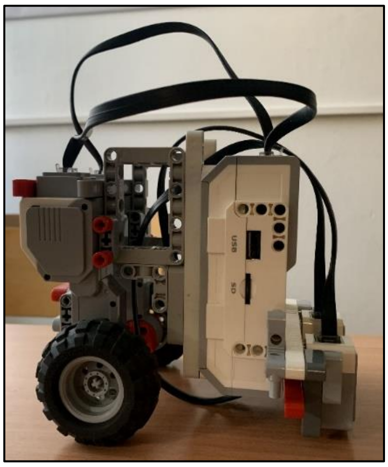
The size of the court is 1.5 m x 1.5 m. In reality, all of this can be measured in kilometers, since the robots can independently scan an area of several square kilometers.

In the implemented project, not only the swarm intelligence principle is significant, but also the communication technique, as two different systems (EV3-ARDUINO) were connected.

HARDWARE

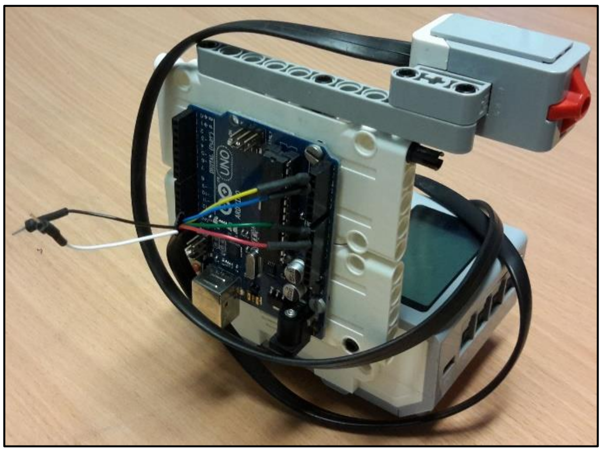
In our model we use 4 identical robots. They each have an ev3 brick, 2 color sensors, and 2 large motors. They use their color sensors to navigate the colored grids. We differentiate between each robot using various colors. We built a robot which is relatively small and simple, but on the other hand can fit the needed electronics. The robots are built using only LEGO parts.

Robot entity

Robot swarm

The server is an EV3 brick connected to an Arduino Uno microcontroller. The devices are connected with a sensor port and 2 digital pins on the Arduino. We use the i2c communicatiuon protocol between the devices. The Arduino uses serial communication to exchange data with the computer. The EV3 brick maganegs the connection and data transfer between the individual robots.



SOFTWARE

Softver on the robot

We use different programming languages, like Python and Java for the EV3 robots. We also use a C based programming language for the Arduino system.
The whole program can be divided up to 3 segments:

- positioning,
- measurment,
- communication.

These 3 segments are repeated during the mapping of the area.

Each robot runs the same identical code, so it complies with the rules of swarm intelligence.

The model uses a Cartesian coordiante system, with a 12 by 12 grid. The gridlines have two colors green and red other than the default black, to determine the direction.

We started with a functions. It follows the lines and navigates through the grid with the help of two colour sensors. One to follow the main black line, and the other to calculate its actual position. This is the cornerstone of our entire code.

The robots begin their movement, and complete a snail like pattern in a 6x6 square, while continously sending their coordinates and measured colors to he server.

Initialization part of Python code on robots

```
#!/usr/bin/env pybricks-micropython
from pybricks.hubs import EV3Brick
from pybricks.ev3devices import (Motor, ColorSensor)
from pybricks.parameters import Port, Stop, Direction
from pybricks.tools import wait, StopWatch
from pybricks.robotics import DriveBase
from pybricks.media.ev3dev import SoundFile, Image
from pybricks.messaging import BluetoothMailboxClient, TextMailbox

ev3 = EV3Brick()
lm=Motor(Port.B,Direction.COUNTERCLOCKWISE)
rm=Motor(Port.C,Direction.COUNTERCLOCKWISE)
robot=DriveBase(lm, rm, 56, 98)
lcol=ColorSensor(Port.S3)
rcol=ColorSensor(Port.S2)
text= Image('_screen_')
mytime= StopWatch()
red = 'Color.RED'
white = 'Color.WHITE'
black = 'Color.BLACK'
green = 'Color.GREEN'
colorsLine = [red, green, black]
```

Python code responsible for sending data on robots

```
client = BluetoothMailboxClient()
mbox = TextMailbox('mail', client)

def sendung(x,y,c): #x, y, color
    uzenet = str(x) + str(y) + str(c) + '1'
    mbox.send(uzenet)
```

The Python code responsible for the movement of the robots

```
def go(g,lista,irany):
    k=0
    vonal=0
    if irany % 4 == 0:
        lista[1] -= 1
    elif irany % 4 == 1:
        lista[0] += 1
    elif irany % 4 == 2:
        lista[1] += 1
    else:
        lista[0] -= 1
    lista[2]=lcol.color()
    print(lista,file=f)
    while k<g:
        if rcol.reflection()<30:
            lm.run(150)
            rm.run(100)
        else:
            rm.run(150)
            lm.run(100)
        if lcol.reflection()<30 and vonal==0:
            k=k+1
            vonal=1
            mytime.reset()
            if irany % 4 == 0:
                lista[1] -= 1
            elif irany % 4 == 1:
                lista[0] += 1
            elif irany % 4 == 2:
                lista[1] += 1
            else:
                lista[0] -= 1
            print(lista,file=f)
```

```
            #sendung(lista[0],lista[1],lista[2])
        if mytime.time() > 400 and vonal == 1:
            vonal=0
            lista[2]=lcol.color()
    robot.stop(Stop.BRAKE)
```

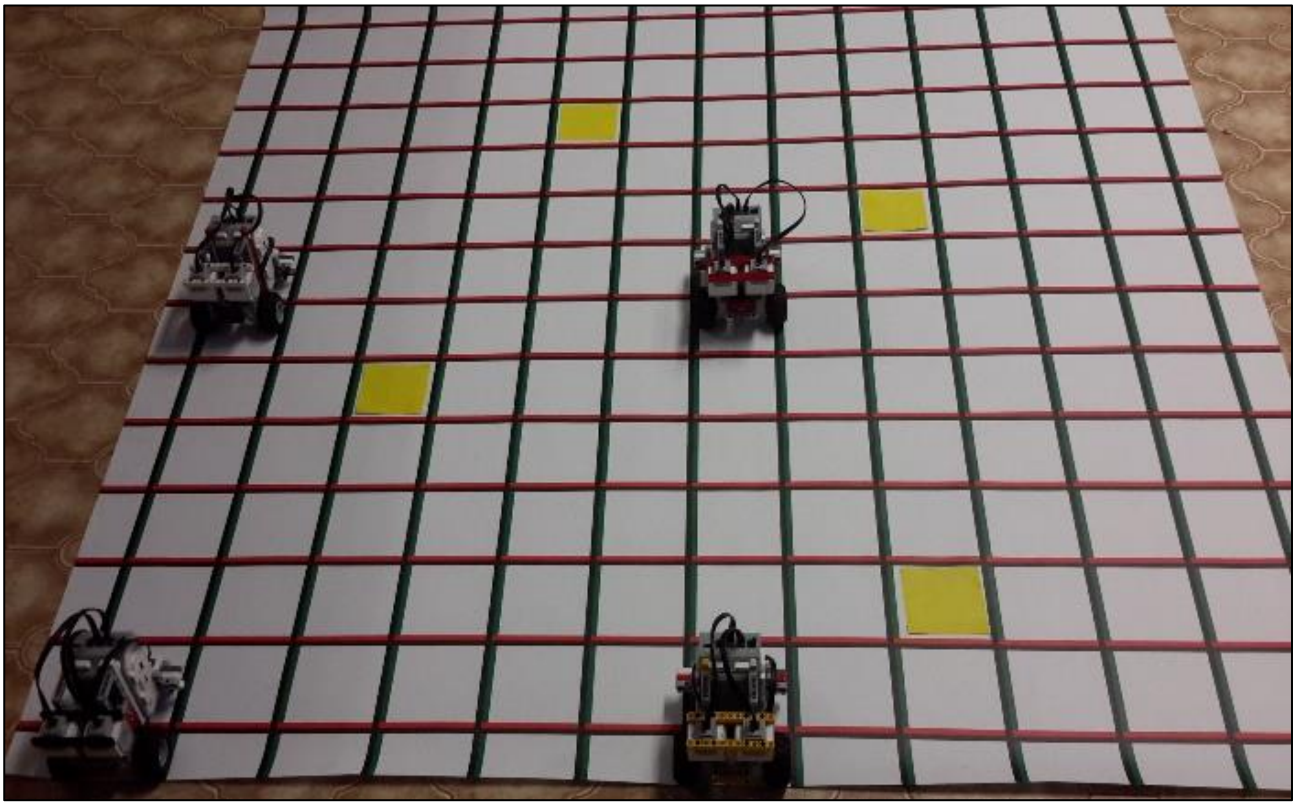
Softver on the server – Communication of robots

In our model the communication between the robots is implemented with a bluetooth server-client network and it connects to the computer via an ARDUINO with serial port. In real life the Arduino could operate the sound transmitters and it can be used as a server as well.
Currently the server and the clients are running ev3-micropython. The server brick is connected to the Arduino with a custom cable and we use the i2c protocol. The reason for the arduino and the server brick is the communication protocol. It would be much complicated to manually decode the bluetooth message structure in the ev3 and the connection can get really unstable if we connect the bricks directly to the computer.

The messages between the ev3 bricks are based on the text mailbox system of the ev3. The clients send a 4 character long message to the server mailbox. The message contains the following data:

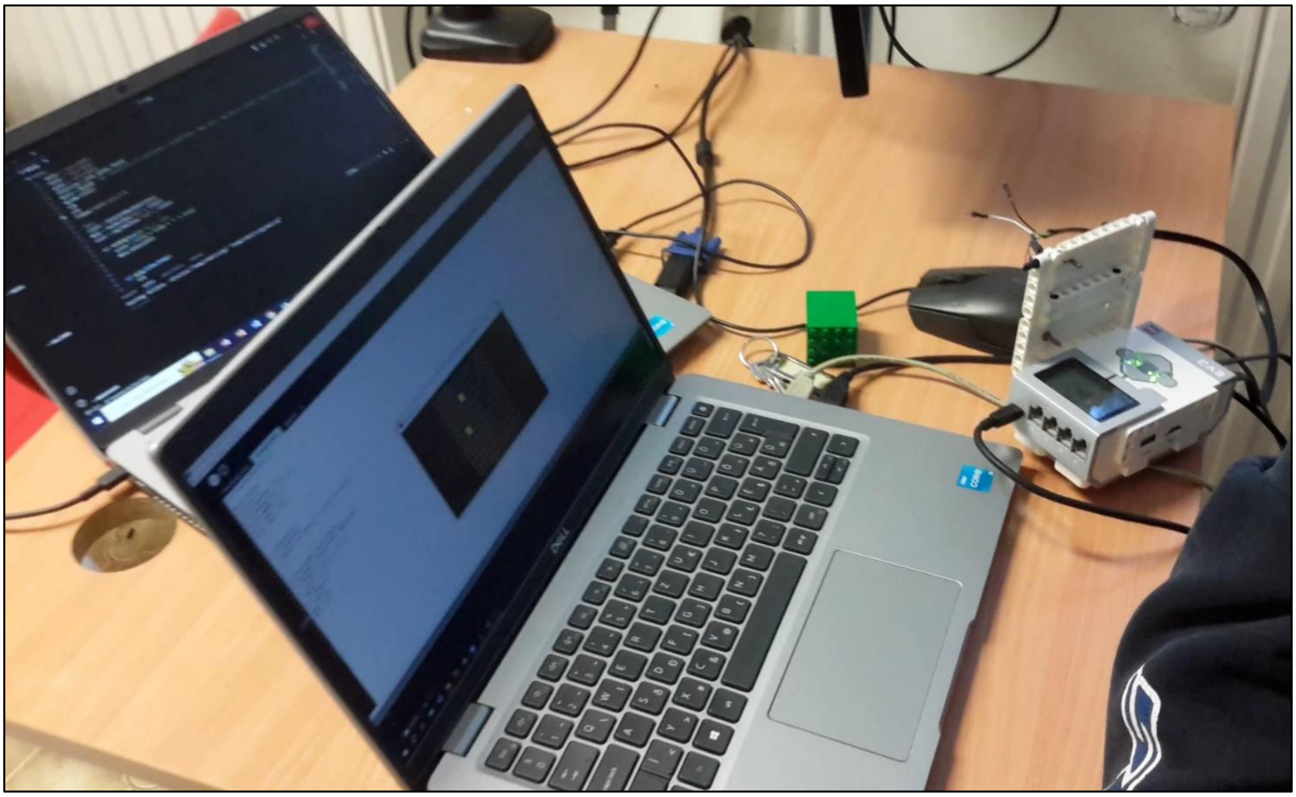
- x position
- y position
- color at current position
- client id

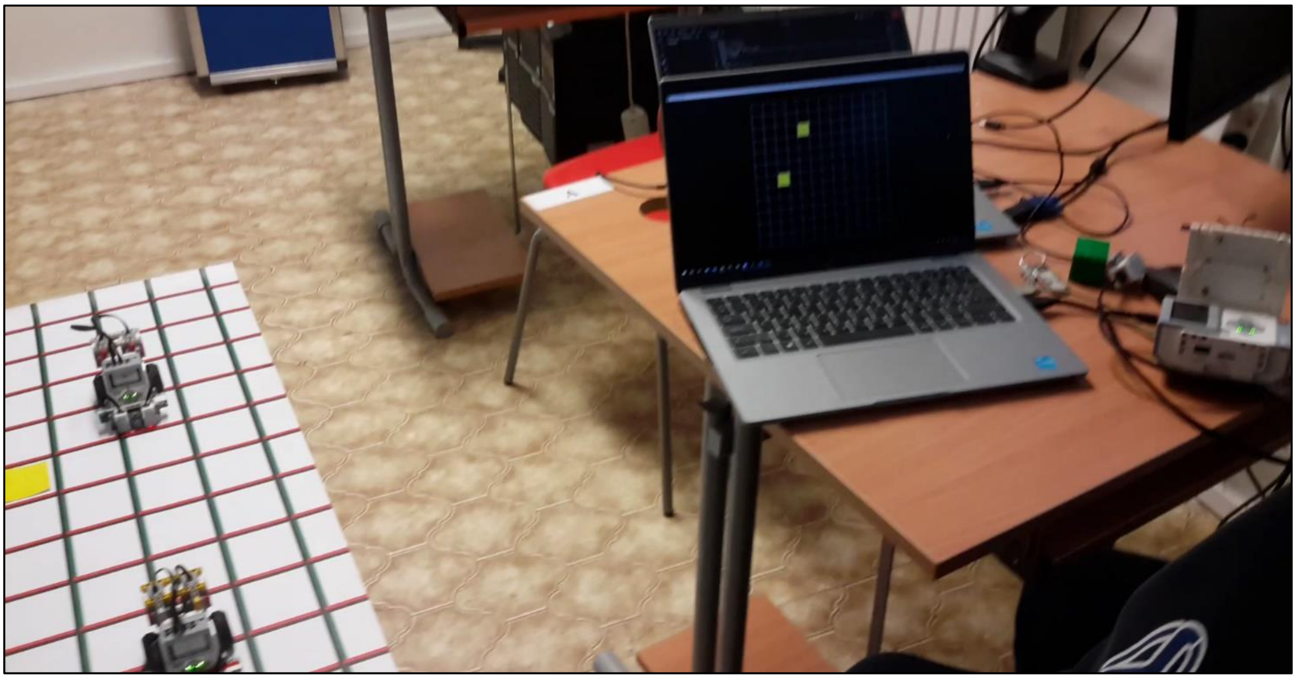
These are all numeric values ranging from 0 to 9 so we can combine these values into a string. In the decoding process we split the characters and convert back to integer. After the processing it can be displayed on the screen. The display program also highlights the robots' current position. The other task of the program is to identify the robots. Every individual robot has a different name and the program is identical on every robot. The robot id is made by doing a query of the robot's name and a dictionary converts it to a number.
The robots count the coordinates relative to its starting position, because this way they can run the same code. In the display program there is a list of the starting positions of the different robot ids and we add these to the realtive coordinates. After the operation the coordinates are the absolute positions of the robots and it can be displayed on the grid.



The starting of the robots is synchronized, they wait for a start signal from the server. This is a message with a logic(boolean) mailbox.

The server





Python code on the server responsible for establishing the connection

```
ev3 = EV3Brick()
server = BluetoothMailboxServer()
device = I2CDevice(Port.S1, 0x02)
ts = TouchSensor(Port.S2)

mailbox = TextMailbox("mail", server)
start = LogicMailbox("start", server)
enter = 12
```

```
a = enter.to_bytes(1, "big")

server.wait_for_connection(4)

print("ready")

pr = False
while not pr:
    pr = ts.pressed()
    start.send(pr)
```

Java code running on the laptop to display the data graphically

```
void drawFrame(int offset[], int n) {
  stroke(255);
  float   w = (width - offset[0] - offset[1])/(n+1);
  float   h = (height - offset[2] - offset[3])/(n+1);
  if (width>height) {
    offset[0] = abs((width-height)/2);
    offset[1] = abs((width-height)/2);
    offset[2] = 0;
    offset[3] =0;
  } else {
    offset[2] = abs((width-height)/2);
    offset[3] = abs((width-height)/2);
    offset[0] = 0;
    offset[1] = 0;
  }
  for (int i = 1; i<n+1; i++) {
    line(w*i + offset[0], w + offset[3], w*i + offset[0], n*w + offset[3]);
    line(h + offset[0], h*i + offset[2], n*h + offset[0], h*i + offset[2]);
  }
}

void setColor(float x, float y, int r, int g, int b, int offset[], int n) {
  constrain(x, 0, n);
  constrain(y, 0, n);
  float   w = (width - offset[0] - offset[1])/(n+1);
  float   h = (height - offset[2] - offset[3])/(n+1);
  noStroke();
  fill(r, g, b);
  rectMode(CORNERS);
  rect(w*(x+1) + offset[0]+1, h*(y+1) + offset[2]+1, w*(x+2) + offset[0],h*(y+2) + offset[2]);
}
```

The C code responsible for receiving data on the Arduino system

```
#include <Wire.h>
#define SLAVE_ADDRESS 0x02
void setup()
{
  Serial.begin(9600); // start serial for output
  Wire.begin(SLAVE_ADDRESS);
  Wire.onReceive(receiveData);
  Wire.onRequest(sendData);
}
int val, flag = 0;
void loop()
{
  if (flag == 1) {
Serial.println(val);
flag = 0;
  }
}
void receiveData(int byteCount)
{
  while (Wire.available() > 0)
  {
    val = Wire.read();
    flag = 1;
  }
}
```

Usability of the project

The project was based on existing mini submarine models. Their main technical parameters from the point of view of the project:

- 100 m diving depth
- 2-3 hours of battery life
- 5-6 km/h speed

Taking these parameters into account, the area that can be searched by one individual of the submarine swarm is 30-40 km^2. So the scale of our test track is 10000:1.

This can be suitable, for example:

- For checking the water quality of stagnant waters, harbors and slow rivers, searching for sources of pollution, investigating the spread of pollution
- For uncovering structural defects in large docks and ports. In this case, a camera is placed on the submarine, which records the footage (photos, video).
- Investigation of the effect of undersea heat sources and volcanic eruptions on water
- Mapping underwater geological conditions
- …

With the help of swarm-based detection, an area of up to 200 km^2 can be examined in 2-3 hours.

The database built from the collected biological and topological characteristics can be continuously expanded, so that conclusions can be drawn regarding typical trends for research purposes.

Measurement of water components to predict biological risks

Our system can be used for measuring various characteristics of water. Firstly it can measure the oxigen level of lakes or seas. This is important because many animals and plants living in water are sensitive tot he oxigen level (https://www.nytimes.com/2023/06/11/us/dead-fish-texas-climate-change.html). The solubility of oxygen decreases if the temprerature rises. This can lead to serious problems, because of global warming. Other measurments could incule water salinity, PH, which is also important for the wildlife, and it't changing could effect their habitat drastically, conductivity, and ion concentrations. We tested different digital sensors in water, and they proved to be useful.

Business model – StartUp

Our project is not yet suitable for building a business model on.

We tested the feasibility of the concept with calculations, but there are many parameters that can only be tested on an experimental basis. E.g.: How the flow affects the propagation of the communication signal. How accurate positioning can be done in practice. (An accuracy of 5-10 m is sufficient.)

Our model illustrates the practical operation of the swarm intelligence principle.

It is worth starting the practical implementation by building an individual. The signal buoys are also needed for testing.

If the tests are successful and the final construction hardware structure has been formed, then the software development of the collaboration is the task after the swarm is built.

Then the production preparation can follow. All of this is preceded by a market research to see if it is worth embarking on the development. The target audience can be planned based on the options presented in the previous chapter.

Estimating the hardware price of a robotic unit:

- Mini Submarine: $5,000
- Special electronics: $1,500
- Electronic buoy (for positioning): $400

It is advisable to create a team of at least 4 individuals and 3 buoys are required to determine the position.

Testing is an important component of development. For this, access to different test environments is an additional cost.

Software development is an easier problem to solve, but it must be run in parallel with testing.

Market research results and developments may be followed by market launch. Here, the goal is primarily to build a system that can initially be rented together with the associated services (e.g. professionals).

SUMMARY

In our project, we examined the possibilities of creating a robot swarm consisting of mini-submarines.

We proved with calculations that underwater communication is possible with sound-based signal sequences. Underwater communication is not easy, so we did not find any working examples of underwater robot swarms.

The physical creation of a submarine swarm was not intended. The goal was to model the behavior of a swarm of robots based on biological systems.

We modeled this with a swarm of 4 EV3 robots. We used an Arduino-EV3 hardware system to implement the communication. We have successfully implemented the communication between the two systems with different structures.

With a presentation signal, the data measured by the robot swarm are displayed in real time on a monitor (projector). In the real project, this is not absolutely necessary, it is sufficient to collect the data. Determining the measurement position is important for creating an accurate database. That is why communication is necessary.

With the completed system, an area of 200 km^2 can be examined in 2-3 hours at a depth of 100 meters.

We have tried to present areas in which the robot swarm can operate effectively. The most important thing seemed to be the examination of the various parameters of the water, which is also important in terms of forecasting and impact assessment in the light of environmental changes (see the articles cited in the study).

We used three different programming languages for programming: Python, Java, C.

Our implemented model contains a total of 5 EV3 and an Arduino microcontroller.