

STEM Games 2019



Engineering

UNDERWATER HABITATS

a problem by

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Arena introduction

First of all, I would like to welcome all the contestants that will be competing in 2019 STEM Games engineering arena!

This year's task focuses on the underwater habitats and logistical problems around them. Underwater habitats can be permanent and semi-permanent, located at the sea beds. They provide all facilities required for the human survival such as sleeping, eating and attending to personal hygiene. Their most common use is for the scientific research, exploring the biology of the deep sea life and for the geological research of the ocean tectonic plates. We also learned a lot about the life and technological problems dealing with the high pressure environments. By the sea levels rising up the underwater habitats may become widespread, not only for scientific research, but also as a permanent home for people. Aquanauts, as they are called spend between couple of weeks to a few months underwater. Future projects that would create larger, more comfortable habitats could extend missions to years.

Although the progress is being made in regenerative systems (for water, food and electricity), most of the underwater habitats are not self sufficient, and require the constant influx of the supplies. The logistical problems met here can be compared to those of supplying a space station - the habitats are dependent on the constant support of the surface to keep the habitat running, transporting new supplies and energy.

For that task, usually purpose built submarines are used, since not all submarines are suited for the habitats located in the deeper waters. Those submarines, alongside with the supplies, also transfer people from the surface to the habitats, and rescuing them in the cases of emergencies. The supplies are loaded into the submarines at the sea ports if the habitats are close to them and few trips are needed to transfer the supplies, or from the larger ship located above the habitat, with the submarine completing multiple dives to transfer the supplies.

In both cases some kind of crane is used to load the supplies. The crane should be able to lift the desired load, pick it and drop it in precise locations and in some cases stabilize the load on the rocky seas.

Another problem is the communication off the habitat with either surface, other habitats, or ships sailing above them. Due to the salt content the sea water is slightly conductive and therefore absorbs electromagnetic radio-waves. If the radio communication is needed, ELF (Extremely low frequency) waves are used since they are less affected by the salt water losses, but often it is better to use other solutions.

There are many interesting problems around this, but during this competition we decided to focus on few we found the most interesting.

We want wish you the best luck during the next 3 days!

All the source codes are provided here:
<https://github.com/aoreskovic/StemGamesEngineering2019>

Day 1

2.1 Hydraulic crane - Introduction

Friendly advice: Read everything before solving the task. Task grading is automatic. Submission form for every task is described in task's readme file.

2.1.1 Tasks

The system for which you have to design a controller is the crane shown in the Figure 2.1. The crane consists of a base, two booms (in some crane configurations *Boom 1* is also called *Mast*), two telescopic beams, three hydraulic cylinders, two electric motors and pulley with belt system. The purpose of the crane is to load the submarine with goods and equipment which is to be transported to underwater habitats. Masses of each part of the crane are listed in Table 2.1. **For the sake of simplicity and overall system dynamics, load has the mass $m_{load} = 800.59kg$.**

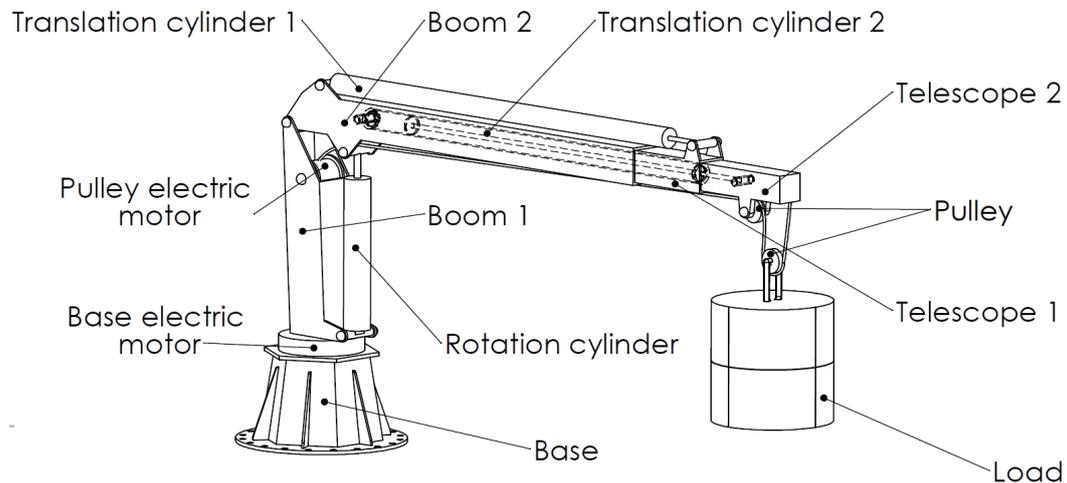


Figure 2.1: Crane configuration, isometry.

Table 2.1: Crane mass

| Part | Mass[kg] | Part | Mass[kg] |
|----------------------------|----------|------------------------|----------|
| Base + Base electric motor | 3794.43 | Rotation cylinder | 105.30 |
| Boom 1 | 536.36 | Translation cylinder 1 | 199.42 |
| Boom 2 | 807.88 | Translation cylinder 2 | 198.24 |
| Telescope 1 | 664.18 | Pulley | 12.25 |
| Telescope 2 | 611.33 | Pulley electric motor | 47.23 |

2.1.2 Hydraulics system(5 points)

Part of the crane is actuated using hydraulic system. The system, as we designed it, is shown in Figure 2.2 and we are aware it has some flaws. Your first task is to think about how you could redesign the system and improve its performance. Concentrate on what you can conclude with what we have given you, i.e. we ask you to propose a redesign of the schematics. You might want to postpone this task until you are done with other tasks and have a better understanding of the system you are working with.

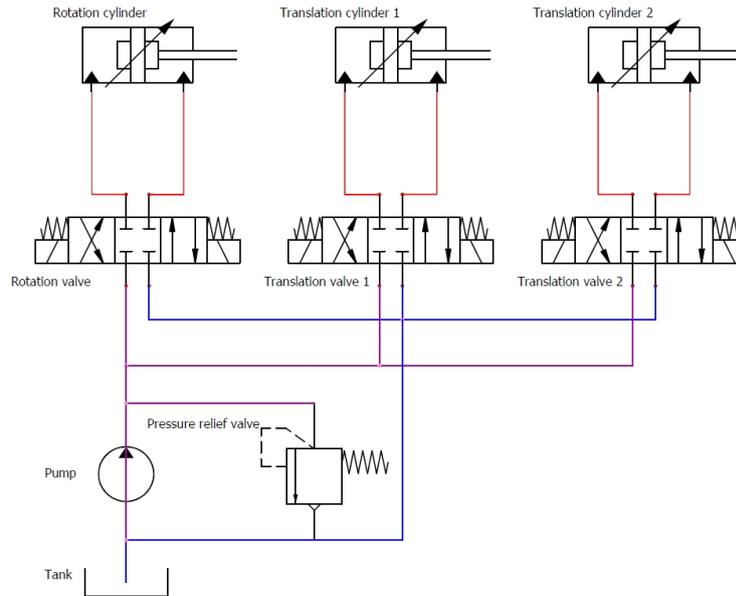


Figure 2.2: Hydraulic system schematics.

2.1.3 Kinematics(20 points)

Kinematics model of the crane is important to ensure that the cargo is precisely placed into the submarine which delivers it to underwater habitats.

Crane configuration and dimensions are shown in Figure 2.3, Figure 2.4 and Figure 2.5. Figure 2.6 shows cylinder configuration with corresponding dimensions given in Table 2.3. Load is shown in Figure 2.7.

Crane configuration has been sketched for $q_1 = 0^\circ$, $d_1 = 194mm$, $d_2 = 369mm$, $d_3 = 437.22mm$ and $q_2 = 0^\circ$. Base coordinate system is defined by red coordinate axes while red dot L represents bottom of the load. Limits of motor angles and cylinder offsets are given in Table 2.2.

Table 2.2: Actuator position limits

| Variable | $q_1 [^\circ]$ | $d_1 [m]$ | $d_2 [m]$ | $d_3 [m]$ | $q_2 [^\circ]$ |
|---------------|----------------|-----------|-----------|-----------|----------------|
| Minimum value | \times | 0 | 0 | 0 | 0 |
| Maximum value | \times | 0.8 | 3.5 | 3.5 | 20000 |

Table 2.3: Cylinder dimensions

| Cylinder | D1[mm] | D2[mm] | D3[mm] | H1[mm] | H2[mm] | H3[mm] |
|-------------|--------|--------|--------|--------|--------|--------|
| Rotation | 180 | 200 | 50 | 30 | 820 | 20 |
| Translation | 80 | 100 | 37.5 | 30 | 3520 | 20 |

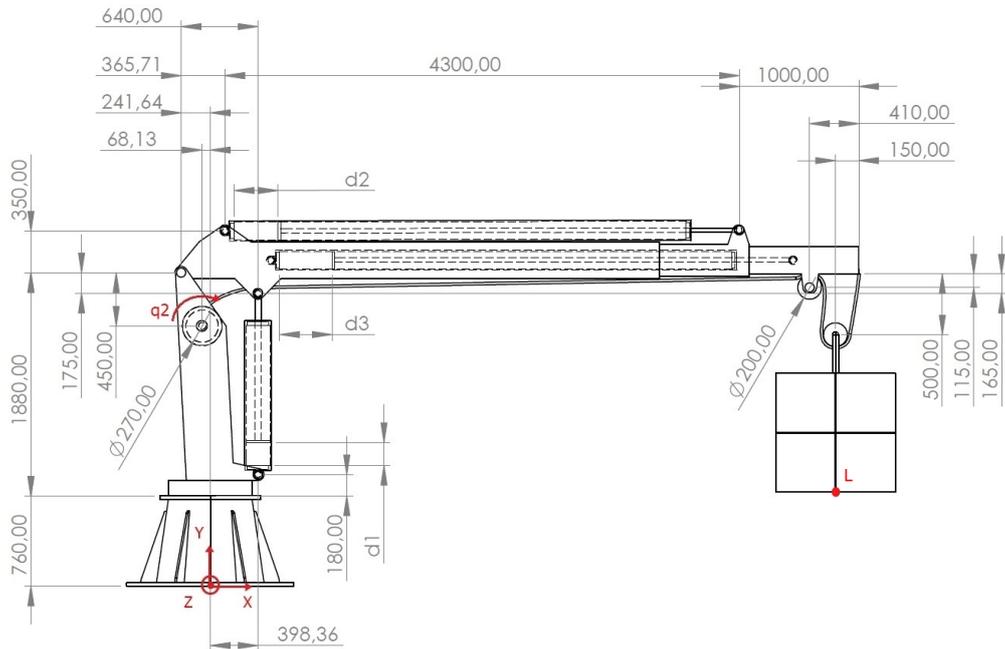


Figure 2.3: Crane configuration, side view.

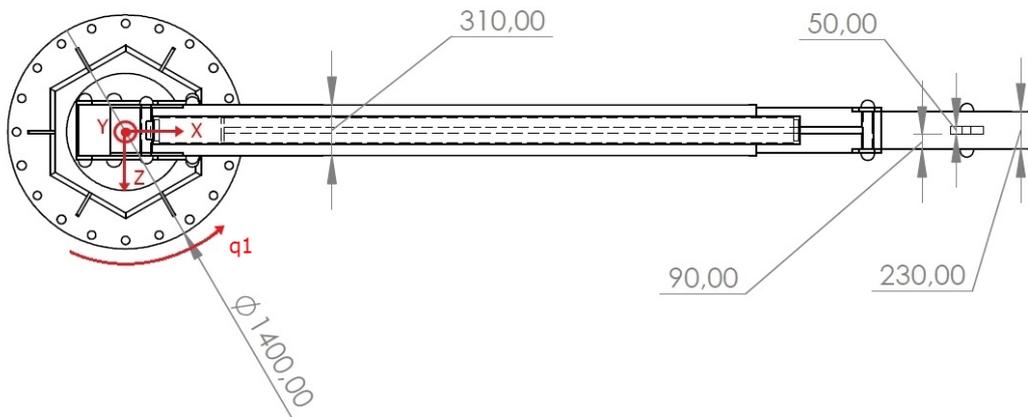


Figure 2.4: Crane configuration, top view.

Direct

To be able to design a controller, first you have to understand kinematics of the crane. Your task is to find the position of the load $L(x_L, y_L, z_L)$ for every combination of electric motor angles and cylinder offsets given in Table 2.4. Be careful calculating the result because **maximum offset** from correct solution we will tolerate is ± 0.25 m. NOTE: Pulley is trickier than it looks.

Table 2.4: Direct kinematics configurations

| Configuration | q_1 [°] | d_1 [m] | d_2 [m] | d_3 [m] | q_2 [°] |
|---------------|-----------|-----------|-----------|-----------|-----------|
| 1. | 0 | 0.194 | 1 | 1 | 1500 |
| 2. | 45 | 0.4 | 0 | 2 | 3600 |
| 3. | 90 | 0.7 | 3.5 | 3.5 | 5000 |

Information on how to submit your solution will be given to you in the *readme* file in task folder. If you have any questions regarding submission of the task, ask your mentors.

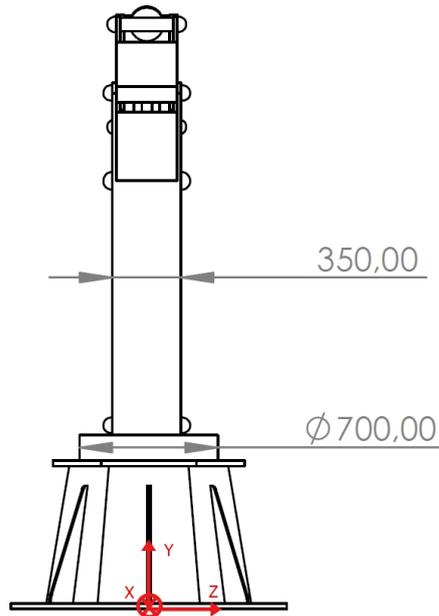


Figure 2.5: Crane configuration, back view.

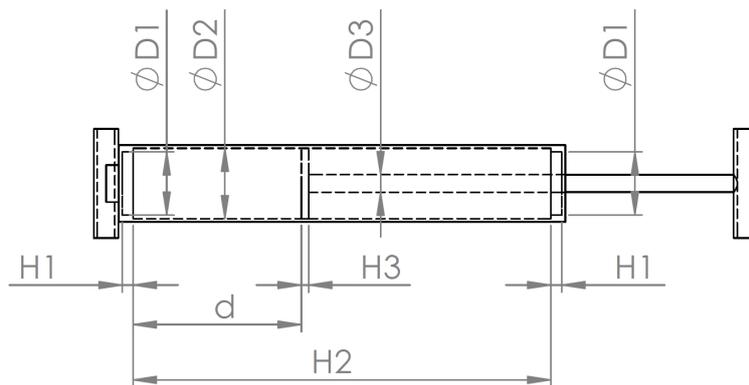


Figure 2.6: Cylinder configuration with dimensions.

Inverse

Next step is to be able to determine kinematic configuration in opposite direction. Based on load positions specified in Table 2.5, determine the corresponding angles and offsets (q_1, d_1, d_2, d_3, q_2) for every given configuration. It is often the case that inverse kinematics has multiple valid solutions, so any valid solution you give will be graded as successful. We will set the crane in configuration position you give us and check if it is inside the maximum offset range of ± 0.25 m from reference point given in Table 2.5.

Table 2.5: Inverse kinematics configurations

| Configuration | x_L [m] | y_L [m] | z_L [m] |
|---------------|-----------|-----------|-----------|
| 1. | 8.0 | -5.0 | 0.0 |
| 2. | -7.5 | -5.0 | 7.5 |
| 3. | 0.0 | 0.5 | 2.5 |

Information on how to submit your solution will be given to you in the *readme* file in task folder. If you have any questions regarding submission of the task, ask your mentors.

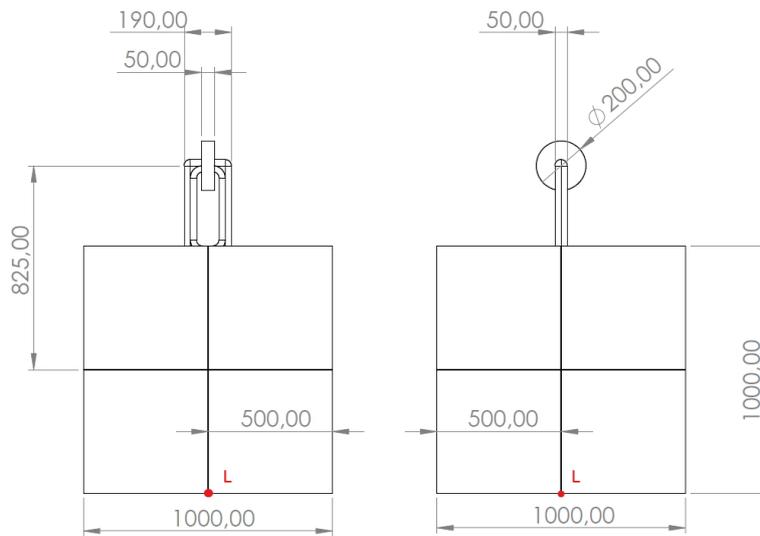


Figure 2.7: Load

2.1.4 Model identification(30 points)

Now when you understand kinematics of the crane, it would be useful to know its dynamic model.

As mentioned before, the crane has 5 actuators. There is a DC motor which is turning the whole crane, one hydraulic actuator performing rotation of booms and telescopes (lifting), two hydraulic actuators used for extension of telescopes and finally a DC motor running belt and pulley system. To successfully drive the crane, you have to determine how it reacts to given inputs. In real systems, you often don't know how system will respond to your inputs, mostly because the model of the system is unknown. In many cases, there are some unknown parameters, order of model is unknown or maybe some parameters are not correct due to the age of system you are controlling, for example, old batteries, old motors, etc.

For this task you will do exactly that! Some of the parameters of the system are unknown and there is no way to measure them so you have to identify models for all crane actuators.

Crane is set to default start position ($q_1 = 0$; $d_1 = 0.194$; $d_2 = 0$; $d_3 = 0$; $q_2 = 0$) and it is ready for driving. Given the known parameters of actuators (Table 2.6), your job is to determine how the actuator will respond. We give you the opportunity to test whatever input signals you want. Inputs for DC motors are in Volts [V] and for hydraulic actuators are valve opening in Meters[m]. Input signal limits are given in Table 2.7. In task's *readme* file you can find a way how to test your input signals and submit your results.

Table 2.6: Electric motor parameters

| Parameter | R[Ω] | L[mH] | k[Vs/rad] | J_{rot} [kgm ²] | n |
|-----------------------|------|-------|-----------|-------------------------------|-----|
| Base electric motor | 2.3 | 20 | 1.3 | 0.2 | 200 |
| Pulley electric motor | 1.7 | 12 | 1.6 | 0.1 | 20 |

Table 2.7: Actuator input signal limits

| Actuator | Base electric motor [V] | Rotation cylinder valve[m] | Translation cylinder 1 valve[m] | Translation cylinder 2 valve[m] | Pulley electric motor [V] |
|---------------|-------------------------|----------------------------|---------------------------------|---------------------------------|---------------------------|
| Minimum value | -120 | -0.005 | -0.005 | -0.005 | -180 |
| Maximum value | 120 | 0.005 | 0.005 | 0.005 | 180 |

We will test your solution with randomly generated test signals. To prevent you from sending us your test signal as an input for identification, every time you send signal for

identification we will create new test signal and **erase all your previous results**. That means that after you decide that your test identification is good enough for you, you should not send another identification signal. As said before, test signals are generated randomly. In total, you will have 5 test cases. Each test case will start in default start position . Identification signal for every actuator is **step** function (Heaviside function) with random step time in interval $[0, T_{sim}]$ and with random value amplitude. Example of one test signal can be found in the task folder.

2.1.5 Crane driving(30 points)

After creating both kinematic and dynamic models of the system, your task is to make it serve its purpose. Crane has to carry a specific cargo from the dock to the submarine cargo space. Desired positions are given in Table 2.5 and you have already calculated inverse dynamics for these coordinates. Crane has to place the load in these points in the order given in Table 2.8.

Table 2.8: Desired crane positions

| P_1 | P_2 | P_3 | P_4 | P_5 |
|-------|-------|-------|-------|-------|
| 3 | 1 | 3 | 2 | 3 |

At each stop, the load has to stay steady for at least $t_{steady} = 5s$ before proceeding to the next one. "Stay steady" in this context means that the bottom point $L(x_L, y_L, z_L)$ of the load has to stay in the norm ball of $R = 0.25$ m around the reference point. Test is finished after the load has been in all requested positions or when the maximum simulation time $T_{sim} = 250s$ has passed. This is measured using test time T_{test} . Final performance cost J_{total} is calculated using the following expression:

$$J_{total} = \frac{5}{24} \sum_{i=1}^5 D_i + \frac{75}{2} T_{total}, \quad (2.1)$$

$$D_i = \begin{cases} \sum_{t=T_{i-1}}^{T_i} \|L(t) - P_i\|, & P_i \text{ reached,} \\ 10000, & P_i \text{ not reached,} \end{cases} \quad (2.2)$$

where T_i is the time in which t_{steady} has been reached in position P_i and $T_0 = 0s$.

Your task is to design five controllers, one for every actuator. Discretization time for every controller is $T_s = 50ms$. Information on how to submit your solution will be given to you in the *readme* file in task folder. If you have any questions regarding submission of the task, ask your mentors.

2.2 DC voltage power supply - introduction(15 points)

For fully functional operation, the crane is equipped with lot of computer based subsystems and electronic devices which operate on DC voltage. To ensure their proper operation the DC voltage has to be stable and without noise. To ensure stable DC voltage, device on Fig. 2.8. is used. Device is composed of several parts as it is shown on the figure. Due to extreme conditions in the system, regulators often fail and components have to be repaired or replaced with proper spare part.

In this task, your job is to:

- find the parts which ensure proper operation of regulator,
- ensure that the output voltage ripple is within the boundaries with proper choice of parts for the low pass filter,
- find the probability of future malfunction in standby redundant system.

Device specifications. Device specifications are provided with the following table. In the first and the second task you have to choose device components. You have to ensure that your choice guarantees that the device operating parameters are within the requirements specified in the table 2.9.

Table 2.9: Device specifications

| PARAMETER | TEST CONDITIONS | VALUE | UNIT |
|------------------------------|--------------------|------------------|------|
| Input voltage (U_{in}) | | 330 | V |
| Output voltage (U_{out}) | $I_{out} = 1$ A | 10 (± 5) % | V |
| Output current (I_{out}) | $U_{in} = 330$ Vpp | 1.0 | A |
| Ripple rejection | (36 kHz) | 78 | dB |

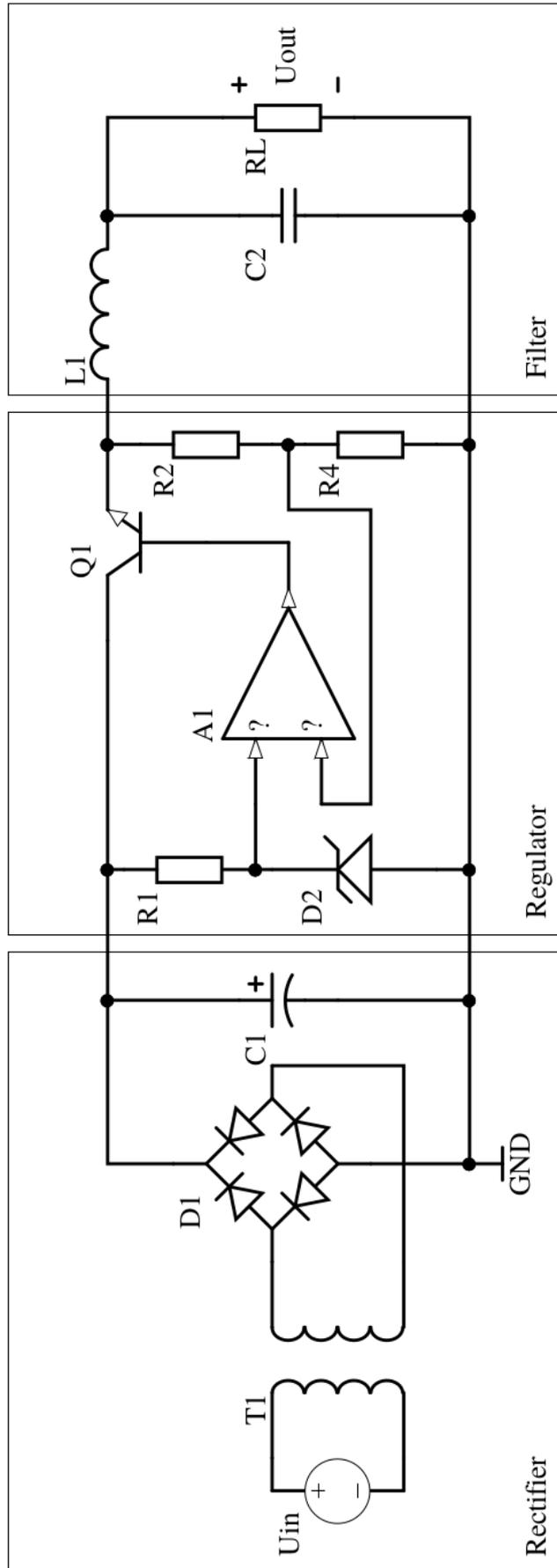


Figure 2.8: DC voltage power supply device schematic

2.2.1 Finding the proper choice of components

As it can be seen from the table 2.10, some components are not determined.

Table 2.10: Device element values

| ELEMENT | PARAMETER | VALUE | UNIT |
|---------|------------------------|-------|---------------|
| T_1 | transfer ratio (n) | 25 | dimensionless |
| D_1 | U_{pn} | 0.6 | V |
| R_2 | Resistance | 1 | M Ω |
| R_4 | Resistance | 470 | k Ω |
| R_L | Resistance | 10 | Ω |
| Q_1 | U_{pn} | 0.6 | V |
| C_1 | Capacitance | 10 | mF |

In this subtask you need to specify resistor R_1 and diode D_2 . Based on the device operating values provided with table 2.9 you have to determine specifications for the resistor R_1 and diode D_2 . You have to find the components from the DigiKey Electronics product database.

There are, however, constraints for your choice of components:

- R_1 has footprint given with figure Fig. 2.9,
- D_2 is a through-hole component.

Your choice is graded in several ways:

- component price,
- correct component voltage, power and current ratings,
- correct component footprint.

As a result, you have to provide part number for resistor and part number for diode, respectively.

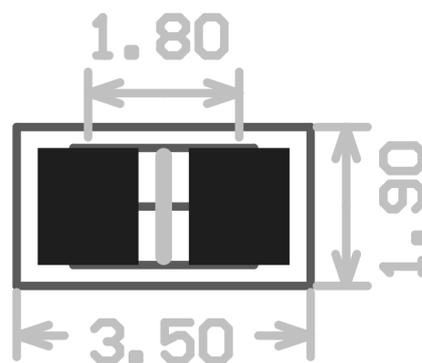


Figure 2.9: Component footprint with dimension in millimeters

2.2.2 LC filter design

To achieve specified ripple rejection at required frequency, design a LC low pass filter which filters output of a regulator. As in previous task you have to provide DigiKey part numbers for LC filter. **Note:** The ripple rejection of the regulator part of the device is 58 dB at 36 kHz.

Again, there are constraints for your choice of components:

- L_1 has no additional constraints (think about already mentioned implicit constraints),
- C_2 has footprint given with Fig. 2.9,
- Q factor has to be equal $\frac{\sqrt{2}}{2}$ for $R_L = 10 \Omega$.

Q factor has to be as close to $\frac{\sqrt{2}}{2}$ as possible.

Your choice is graded in the similar fashion as before:

- price,
- correct inductance and capacitance,
- correct footprints,
- correct current and voltage ratings.

As a result, you have to provide part number for inductor and part number for capacitor, respectively.

2.2.3 Side task: Reliability of the system with redundant power supply

To increase reliability of the power supply system two different linear regulators are linked in configuration which is given with the Fig. 2.10. This configuration is known as passive standby redundancy. Probability of a failure in one regulator is modeled with exponential probability density function. More precisely, probability density function for the first regulator is:

$$f_1(t) = \lambda_1 e^{-\lambda_1 t} \quad (2.3)$$

and for the second regulator:

$$f_2(t) = \lambda_2 e^{-\lambda_2 t} \quad (2.4)$$

Your task is to determine probability density function $f_S(t)$ which gives the probability of failure in system described with Fig. 2.10. As a result provide probability of a failure for $t = 10000 h$ with:

$$\lambda_1 = 1 \cdot 10^{-6} h^{-1}$$

$$\lambda_2 = 2 \cdot 10^{-6} h^{-1}$$

Note: mean time between failures is increased $T_{sf} = T_{1f} + T_{2f}$.

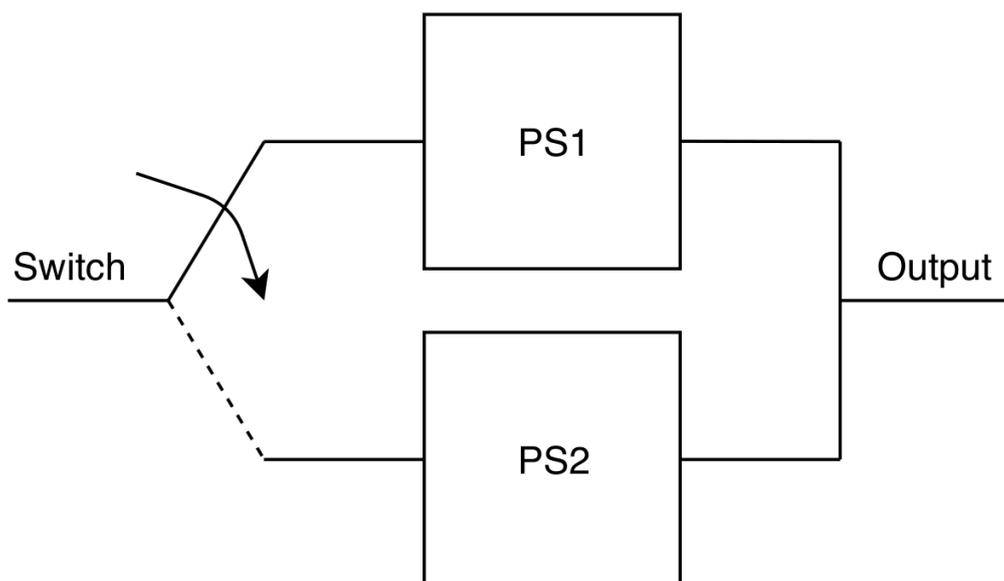


Figure 2.10: Standby system configuration

2.2.4 Solution format

Solution for each task is a plain text document containing requested data. For the tasks 2.2.1 and 2.2.2 text documents need to have two rows. One component part number in each row. Only one row is needed for the task 2.2.3 (requested probability). Name the files `task1.txt`, `task2.txt`, `task3.txt` and put them in the appropriate Google Drive folder.

Additionally, for the task 2.2.3 you have to provide paper documentation which has to contain derivation of $f_S(t)$.

2.2.5 Grading scheme

Tasks are graded in the following manner:

- tasks 2.2.1 and 2.2.2 - up to **5 pts** each (correct components in each task),
- task 2.2.3 - up to **5 pts** - **2.5 pts** for the correct probability and up to **2.5 pts** for correct documentation.

Day 2

3.1 Introduction

The choice of propulsion system type is one of the most important parts in submarine's design process since it determines the ability of fulfilling its purpose. Submarines that perform underwater research activities require endurance and certain flexibility in different littoral conditions. For example, conventional motor propulsion systems, such as diesel electric, when operational, require fresh air intake for driving electrical generator. In this way, a period while a submarine can remain submerged is limited by the power and endurance of the battery system and counts in hours or few days at most. Therefore, when it comes to endurance such systems might not be an optimal choice. Technology that overcomes this drawback is a nuclear power system which offers better endurance (even few months) and speed of the submarines but there are number of disadvantages (very expensive, operational limitations in shallow littoral waters etc.) that make them unsuitable for underwater research activities. The most suitable seems to be so called Air Independent Propulsion systems (AIP systems) which are marine propulsion technologies that allows non-nuclear submarine to operate without access to atmospheric oxygen.

One of the most interesting is definitely French AIP technology so called MESMA (Module d'Énergie Sous-Marine Autonome). This is the AIP system that uses closed-turbine cycle for powering electrical generator and the heat for steam generation is provided by liquid bioethanol combustion in pure oxygen. Combustion of pure bioethanol makes this system ecologically much more acceptable than other systems that use conventional fuels. In this way, virtually silent MESMA exploits all advantages of AIP systems for maintenance of underwater habitats and performing underwater research or training activities.

The assignment can be divided into two steps:

1. Design and dimension main components of the propulsion system,
2. Define operational characteristics of some components.

After the first step you will be given a full model of propulsion system with the components you selected which will help you define operational characteristics of some components. Detailed description of the system components is given in the next section.

Engineers, good luck!

3.2 Power generation system description

3.2.1 The submarine

Today's assignment is to design a MESMA power generation system for submarine propulsion for a given submarine hull which consists of outer and inner shell, showed on Figure 4.11. Inside inner shell there is a reserved space of fixed volume consisting of five compartments; power system compartment (compartment 5), bioethanol tank (compartment 4), liquid oxygen tank (compartment 3), cargo storage (compartment 2), and crew deck (compartment 1).

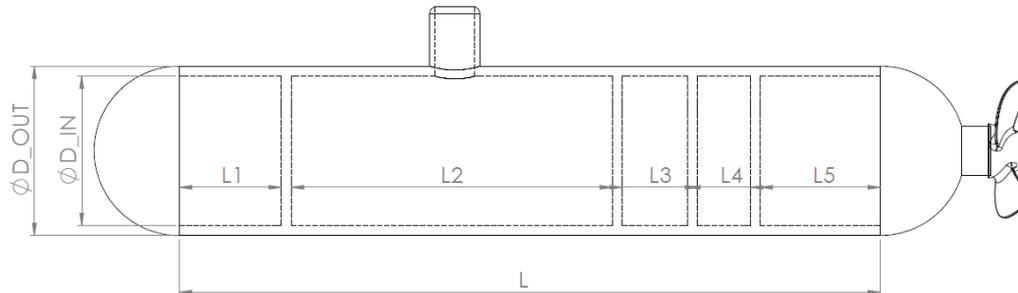


Figure 3.1: Submarine dimensions

The following dimensions are given:

- $L = 18$ m
- $D_{OUT} = 3.4$ m
- $D_{IN} = 3$ m
- $L_1 = 2$ m

D_{IN} is used for the tank volume calculation.

Also, dimension L_5 is found as

$$L_5 = (18 \cdot P_{\text{turb}} + 2500)/1000 \text{ [m]} \quad (3.1)$$

where the power P_{turb} is taken in kW. Dimensions L_2 and L_3 depend on the chosen amount of fuel and oxygen.

Team's solutions will be ranked in the following categories:

- Maximum speed
- Maximum range
- Maximum depth
- Available cargo volume

Each category can win you up to 25% of points available for this task. The team that achieved the highest score in each category will be awarded the maximum number of points. The other teams' points will be scaled accordingly.

3.2.2 Power system

Power generation system schematics are shown on figure 3.2.

Submarine power generation system consists of two main circuits; flue gas¹ circuit (red) and steam circuit (cyan). Steam circuit is used for steam production which expands in turbine "Turb" providing necessary power for the "Generator" used for charging the batteries for submarine propulsion. The flue gas circuit is used to provide necessary heat flow for evaporating and superheating the steam for the turbine. Flue gas

¹combustion exhaust gas

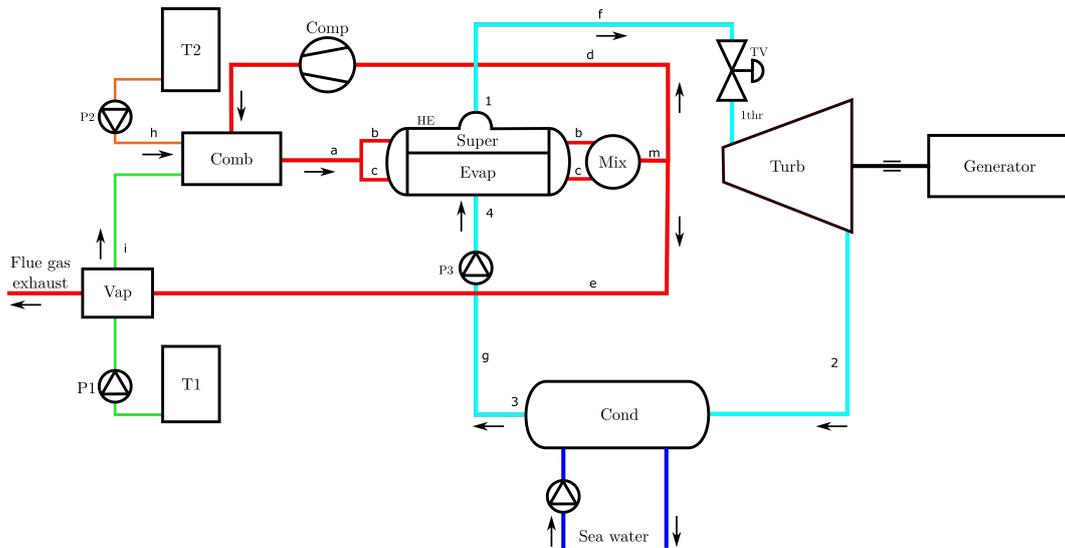


Figure 3.2: Power generation system

is generated in the combustion chamber "Comb" in which energy is released by ethanol combustion in pure oxygen.

Liquefied oxygen and ethanol fuel are stored in separate tanks "T1" and "T2", respectively. While pump P2 delivers fuel stream "h" to combustion chamber "Comb", cryogenic pump P1 delivers liquefied oxygen stream "i" to oxygen vaporizer "Vap" where it vaporizes and enters combustion chamber "Comb" in stoichiometric ratio at which fuel combustion is, by assumption, complete without any excess oxygen. Flue gas temperature at the outlet from the combustion chamber (stream "a") is controlled by return stream of cooled flue gas "d" by compressor "Comp" and should never exceed maximum allowed flue gas temperature

Flue gas stream "a", which exits combustion chamber "Comb" enters heat exchanger "HE" used for water evaporation and steam superheating. Therefore, heat exchanger "HE" comprises two sections; an evaporation section "Evap" and superheating section "Super". Total flue gas mass flow which enters heat exchanger "HE" is divided into two flue gas streams "b" and "c". Stream "c" flows through evaporation ("Evap") section and stream "b" flows through superheating ("Super") section in parallel configuration. On heat exchanger exit, two flue gas parallel streams "b" and "c" are adiabatically mixed in mixing chamber "Mix" forming flue gas stream "m". Part of stream "m" is returned by compressor "Comp" to combustion chamber "Comb" as stream "d" to prevent overheating (maximum allowed flue gas temperature), while the rest (stream "e") is used for oxygen evaporation in heat exchanger "Vap" and evacuated outside submarine.

Heat exchanger "HE" is a pool boiling type apparatus which means that liquid water in the evaporating section is at rest and is evaporated by the flue gas that passes through a tube bundle in the evaporating section. The exact amount of steam that is evaporated in evaporation section "Evap" (which corresponds to the steam mass flow of stream "g") is then superheated in superheating section "Super" of heat exchanger "HE" producing the superheated steam "f". Superheated steam (stream "f") passes through throttling valve "TV" and enters the steam turbine "Turb" where mechanical power is produced by steam adiabatic expansion to condensation pressure p2. After the expansion, low pressure steam condenses in sea water cooled condenser "Cond" and is returned to high pressure evaporator "Evap" by condensate pump "P3".

Following sections provide a detailed description of every part of power generation system that should be modeled.

It is very important that system states are in allowed limits.

- Maximum temperature at combustion chamber "Comb" exit (850°)
- Maximum steam temperature at turbine "Turb" inlet (Excell table 1)

- Minimum vapor fraction on turbine “Turb” outlet should not exceed (0.9)
- Evaporator “Evap” erosion (given by the equation 3.28)
- Superheater “Super” erosion (given by the equation 3.28)
- System malfunction due to insufficient generated power (given by the equation 3.10)

Each failed test will cause 40% point reduction in the given test category.

3.2.3 Turbine

A Steam Turbine is a mechanical device in which thermal energy is extracted from pressurized steam by its adiabatic expansion and is transformed to mechanical work. Therefore, for a given mass flow rate of steam q_m , power P generated by steam turbine is defined:

$$P = q_m(h_1 - h_2), \quad (3.2)$$

where

- q_m is steam mass flow rate,
- h_1 is steam specific enthalpy at turbine inlet,
- h_2 is steam specific enthalpy at turbine outlet.

Turbine steam swallowing capacity mass flow rate q_m at given pressures and inlet temperature can be expressed by Stodola’s Ellipse equation:

$$q_m = \frac{K}{\sqrt{T}}(p_1^2 - p_2^2)^{\frac{1}{2}}, \quad (3.3)$$

where:

- K is Stodola’s coefficient $\left[\frac{\sqrt{\text{K} \cdot \text{kg}}}{\text{s} \cdot \text{bar}} \right]$,
- p_1 is turbine inlet pressure [bar],
- p_2 is turbine outlet pressure [bar],
- T is turbine inlet absolute temperature [K].

Steam turbine isentropic efficiency

Turbine isentropic efficiency η is defined as the ratio between enthalpy drop at actual turbine expansion and enthalpy drop at isentropic expansion between inlet and outlet turbine pressure p_1 and p_2 .

$$\eta = \frac{h_1 - h_2}{h_1 - h_{2s}}. \quad (3.4)$$

Steam turbine isentropic efficiency depends upon mean steam volume flow rate q_v according to the following equation:

$$\eta = aq_v^2 + bq_v + c, \quad (3.5)$$

where q_v is geometric mean of volume flow rates at turbine inlet ($q_{v,in}$) and at outlet in case of isentropic expansion ($q_{v,out,s}$).

$$q_v = \sqrt{q_{v,in} \cdot q_{v,out,s}}, \quad (3.6)$$

Turbine efficiency is highest at its nominal design point for which pressures (p_1 , p_2) and inlet temperature T_1 are given in Excel Table 1, while nominal flow rate is defined by Stodola’s Ellipse equation 3.3. Turbine can operate at other conditions (off design turbine performance with lower, i.e. higher mass flow rates than the nominal) with the cost of reduced efficiency, provided that these conditions are not outside permitted values.

Off design turbine performance

Lower mass flow rate

Steam throttling is a common way for reduction of power produced by steam turbine. By reducing fuel pump "P2" and oxygen pump "P1" speed accordingly when power demand is lowered, fuel consumption and evaporated steam mass flow rate are decreased. In conjunction with steam flow rate decrease, throttling valve "TV" orifice is constricted to reduce turbine inlet pressure $p_{1,thr}$ to a value which satisfies Stodola's Ellipse law 3.3 for given decreased mass flow rate q_m . In a throttling process, superheated steam which exits heat exchanger "HE" is throttled to lower pressure $p_{1,thr}$, while steam enthalpy is conserved.

$$h_{1,thr} = h_1, \quad (3.7)$$

$$p_{1,thr} = p_1, \quad (3.8)$$

$$T_{1,thr} = T(p_{1,thr}, h_1) < T_1. \quad (3.9)$$

Side effect of throttling is a temperature reduction which corresponds to the state of conserved enthalpy h_1 at throttled pressure $p_{1,thr}$. Pressure and temperature are both part of a Stodola's Ellipse law 3.3 which means they need to simultaneously satisfy Stodola's Ellipse law 3.3 and enthalpy conservation of a throttling process from state "1".

By throttling, turbine inlet pressure and inlet temperature are reduced which decreases available isentropic power of turbine. Turbine efficiency described by equation 3.5 is also decreased at partial turbine load.

Higher mass flow rate

In case that power demand is increased, turbine can be overloaded by steam mass flow q_m greater than nominal. This is achieved by fuel pump "P2" and oxygen pump "P1" speed increase which causes increased fuel consumption and evaporated steam mass flow. When turbine is overloaded, steam flow bypasses few initial turbine stages which enables increased steam consumption, although with reduced turbine efficiency described by equation (3.5). To accurately model this effect is out of scope of this assignment. Therefore, it is assumed in overload working mode that turbine inlet values of pressure and temperature remain nominal, i.e. there is no change at throttling valve due to increased steam mass flow rate q_m . The only effect of increased q_m is turbine efficiency reduction as described by equation 3.5.

Restrictions of steam turbine operational parameters are following:

- Steam temperature at turbine inlet should not exceed temperature $\vartheta_{turb,max}$,
- Define operational characteristics of some components.

Turbine design parameters are given in Excel Table 1.

Minimum required turbine power

The minimum power which the turbine has to provide for the submarine for it to remain operational is defined by

$$P_{min} = 2 + 0.05 \cdot P_{nom} \text{ [kW]} \quad (3.10)$$

where P_{nom} is the nominal turbine power, given in Excel Table 1 in kW.

If the power generated by the turbine falls below the value of P_{min} , the submarine will fatally malfunction.

Submarine velocity is calculated based on the power remaining for propulsions, as

$$v_{sub} = 2.0135 \cdot P_{prop}^{0.3518} \text{ [kn]} \quad (3.11)$$

where P_{prop} is taken in kW, and it is equal to

$$P_{prop} = P_{turb} - P_{min} \quad (3.12)$$

3.2.4 Heat exchangers

Heat exchanger is a device whose purpose is to transfer heat from warmer fluid stream to colder stream. There are three heat exchangers in the power generation system: heat exchanger "HE" which is divided to superheating and evaporative section, condenser "Cond" and oxygen vaporizer "Vap". Condenser "Cond" and vaporizer "Vap", whose performance will not be evaluated in this task are assumed to be regulated accordingly in each time step with the current need of the power generation system.

Heat exchanger "HE"

Heat exchanger "HE" is used for steam evaporation and superheating in two corresponding sections by hot flue gas from combustion chamber ("b" and "c" stream). It is shell and tube type with flue gas passing through tubes in each section.

Heat flow exchanged in each of two heat exchanger sections is described as:

$$\Phi = A \cdot k \cdot LMTD, \quad (3.13)$$

where:

$LMTD$ is logarithmic mean temperature difference, k is overall heat transfer coefficient, A is total heat exchange area of the section. Assume superheating section of heat exchanger is counter-flow.

In addition to LMTD method, rate of heat transfer can be determined using NTU method. For counter-flow heat exchanger effectiveness is calculated as:

$$\pi_1 = \frac{1 - \exp((1 - \pi_3)\pi_2)}{1 - \pi_3 \exp(-(1 - \pi_3)\pi_2)}, \quad (3.14)$$

Dimensionless parameters π_1, π_2, π_3 are defined as follows:

$$\pi_1 = \frac{\theta'_1 - \theta''_1}{\theta'_1 - \theta'_2}, \quad (3.15)$$

$$\pi_2 = \frac{kA}{C_1}, \quad (3.16)$$

$$\pi_3 = \frac{C_1}{C_2}, \quad (3.17)$$

where C is stream heat capacity.

Index 1 corresponds to stream with lower heat capacity, index 2 to stream with higher heat capacity, superscript ' to stream inlet state in heat exchanger and '' to outlet state.

Flue gas, which is divided into two streams "b" and "c" enters evaporation "Evap" and superheating "Super" section at equal temperature and flows through tubes in one pass. Flue gas mass flow through evaporative and superheating section of heat exchanger is defined as:

$$q_{m,fg,evap} = \text{evap}_{fr} \cdot q_{m,fg}, \quad (3.18)$$

$$q_{m,fg,super} = (1 - \text{evap}_{fr}) \cdot q_{m,fg}, \quad (3.19)$$

Where: evap_{fr} is flue gas fraction of stream "c" to total flue gas stream "a" mass flow and is assumed constant throughout system operation. Its value can be selected between 0 and 1. $q_{m,fg}$ is total flue gas mass flow rate (stream "a") . $q_{m,fg,evap}$ is evaporation section mass flow rate (stream "b") $q_{m,fg,super}$ is superheating section mass flow rate (stream "c") Heat transfer coefficient on tube side can be calculated by using following simplified convection models.

If the flow is transient or turbulent ($2300 < Re < 5e6$) , mean Nusselt number is defined as:

$$Nu = \frac{f/8 \cdot (Re - 1000) \cdot Pr}{1 + 12.7\sqrt{f/8} \cdot (Pr^{2/3} - 1)}, \quad (3.20)$$

where f is the friction factor, defined as

$$f = \frac{1}{(1.82 \log_{10} Re - 1.64)^2} \quad (3.21)$$

If the flow is laminar ($Re < 2300$), mean Nusselt number is defined as:

$$Nu = 1.86 \left(Pe \frac{d}{L} \right)^{1/3} \quad (3.22)$$

In above equations non-dimensional numbers are

- $Nu = \frac{\alpha d}{\lambda}$ Nusselt number
- $Re = \frac{\rho w d}{\mu}$ Reynolds number
- $Pr = \frac{\mu c_p}{\lambda}$ Prandtl number
- $Pe = Re Pr$ Peclet number

Nusselt, Prandtl and Reynolds numbers and flue gas velocity are calculated using mean flue gas temperature properties between pipe inlet and outlet. All physical properties except density are assumed independent of pressure and its values for pure gases are given in appendix. Flue gas physical properties are calculated as molar average of gases which form flue gas. Density is calculated using ideal gas equation of state.

Evaporation occurs on shell side of evaporative section of heat exchanger. Evaporative heat transfer coefficient on shell side is assumed constant and its value is $\alpha_{ev} = 3500 \frac{W}{m^2 K}$. In superheater section of exchanger, heat transfer coefficient on shell side is also assumed constant and its value is $\alpha_{super} = 70 \frac{W}{m^2 K}$.

Evaporated steam mass flow q_m is determined by heat flow Φ_e exchanged in evaporative part "Evap" of heat exchanger "HE":

$$\Phi_e = q_m (h'' - h_4), \quad (3.23)$$

where h'' is saturated (dry) steam specific enthalpy, and h_4 is enthalpy of subcooled liquid at condensate pump outlet. The same amount of heat flow is received from stream "b" flue gas whose enthalpy decreases.

$$\Phi_e = q_{m,fg,evap} (h_{fg,comb} - h_{fg,evap,out}), \quad (3.24)$$

where $h_{fg,comb}$ is flue gas specific enthalpy at combustion chamber "Comb" outlet $h_{fg,evap,out}$ is flue gas specific enthalpy at evaporative section "Evap" outlet. Flue gas mean molar heat capacities are given in appendix It is assumed that mass flow q_m in current time step flows through superheating section "Super" of "HE", turbine "Turb", condenser "Cond" and condensate pump "P3".

Evaporated steam mass flow q_m , whose value is determined by equation (13) is then superheated at constant pressure in superheater section "Super" of heat exchanger "HE" by exchanged heat flow:

$$\Phi_s = q_m (h_1 - h''), \quad (3.25)$$

The same amount of heat flow is received from stream "c" flue gas whose enthalpy decreases.

$$\Phi_s = q_{m,fg,super} (h_{fg,comb} - h_{fg,super,out}), \quad (3.26)$$

where $h_{super,out}$ is flue gas specific enthalpy at superheating section "Super" exit. Both flue gas streams are adiabatically mixed at heat exchanger outlet in mixing chamber "Mix". Outlet temperature from the mixing chamber is defined by equation:

$$\vartheta_{fg,ret} = \frac{q_{m,fg,evap} \cdot h_{fg,evap,out} + q_{m,fg,super} \cdot h_{fg,super,out}}{q_{m,fg} \cdot c_{p,fg}(\vartheta_{fg,ret})}, \quad (3.27)$$

where:

- $q_{m,fg}$ is temperature after stream "b" and "c" mixing at which part of flue gas is returned to combustion chamber
- $c_{p,fg}(\Theta_{fg,ret})$ is mean specific heat capacity of flue gas between temperature $\Theta_{fg,ret}$ and $0^\circ C$.

Pipe diameter and thickness are given in section 3.2.10.

Value of exchanged heat at both sections depends upon stream inlet conditions, overall heat transfer coefficient k and overall heat transfer area A . Heat transfer coefficient k and area A are influenced by number of tubes in each section and its length which define tube side heat exchanger coefficient and total heat transfer area.

Type and length of tubes at evaporative and superheating section are equal. Number of tubes for each section and flue gas fraction which enters each section can be selected independently.

While designing a heat exchanger, to prevent tube erosion, one must consider that product of flue gas density, ρ , and squared velocity, w^2 , never exceed 6800 Pa, i.e.

$$\rho w^2 < 6800 Pa. \quad (3.28)$$

Condenser

Condenser "Cond" is a heat exchanger which is used for condensation of steam which exits turbine "Turb" at condensation pressure p_2 . During condensation, following heat flow is released:

$$\Phi_{cond} = q_m(h_2 - h'), \quad (3.29)$$

where h' is enthalpy of saturated liquid water at condensation pressure p_2 .

Heat flow Φ_{cond} is rejected to sea water inside condenser "Cond". It can be assumed that condenser "Cond" in the system is properly designed and sea water mass flow at pump "P4" is automatically adjusted to absorb heat flow Φ_{cond} . Therefore, sizing of condenser "Cond" and sea water pump "P4" and its control is not a part of this task and is assumed as ideal. Condensed water always exits condenser "Cond" at saturated liquid state. Maximum sea water temperature at which submarine has to operate is $30^\circ C$, and minimal temperature difference between condensing steam and sea water for given condenser is $15^\circ C$.

3.2.5 Combustion chamber

Combustion chamber "Comb" is enclosed space in which ethanol burns in liquid oxygen. It is assumed to be perfectly insulated. During the combustion, lower heating value of ethanol is converted into flue gas enthalpy. Combustion pressure is at least 1 bar above static pressure evaluated at submarine centerline. Pressure loss from combustion chamber "Comb" to heat exchanger "HE" can be neglected.

In addition to ethanol combustion, combustion chamber "Comb" is used for mixing newly formed flue gas and cooled flow gas which passed heat exchanger "HE" and is returned to chamber "Comb" to prevent overheating. Combustion chamber inlet streams are pure oxygen stream "i" and ethanol stream "h", both at $10^\circ C$ and returning flue gas stream "d" at heat exchanger exit temperature $\Theta_{fg,ret}$. The only outlet stream from the combustion chamber "Comb" is flue gas stream "a" which consists of return flue gas "d" and flue gas newly formed by combustion.

$$q_{m,fg} = q_{m,fg,new} + q_{m,fg,ret}, \quad (3.30)$$

Flue gas outlet temperature is defined by first law of thermodynamics applied to combustion chamber "Comb":

$$\vartheta_{fg,comb} = \frac{\dot{H}_{O_2,in} + \dot{H}_{ethanol,in} + \dot{H}_{fg,ret} + q_{n,ethanol}\Delta H_{md}}{C_{fg}}, \quad (3.31)$$

where

- ΔH_{md} is ethanol lower heating value [kJ/kmol]
- $\dot{H}_{O_2,in}$ is enthalpy of oxygen stream "i" at $10^\circ C$
- $\dot{H}_{ethanol,in}$ is enthalpy of ethanol stream "h" at $10^\circ C$
- $\dot{H}_{fg,ret}$ is enthalpy of returning flue gas at temperature $\Theta_{fg,ret}$
- $q_{n,ethanol}$ is molar flow rate of ethanol stream "h"
- C_{fg} is mean isobaric heat capacity of flue gas stream "a" which exits combustion chamber "Comb"

Flue gas composition is the same in all system parts and is defined by complete combustion of ethanol in pure oxygen.

3.2.6 Fuel and oxygen pumps

Fuel pump "P2" is used to transport fuel to combustion chamber. Pump "P2" has a variable frequency drive which allows precise control of fuel mass flow to combustion chamber. It is assumed that combustion of delivered fuel mass flow is complete and instantaneous. It is also assumed that control of oxygen pump "P1" is linked to pump "P2" in a way that oxygen supply is in exact stoichiometric ratio needed for complete ethanol combustion. Therefore, oxygen pump "P1" dimensioning and control is not a part of this assignment. Fuel pump "P2" speed determines the fuel combustion rate and influences evaporation and superheating of steam in heat exchanger "HE" and finally power P extracted at steam turbine "Turb".

Fuel pump

Fuel pump "P2" is positive displacement pump with variable speed drive. It is used to transport fuel from fuel tank "T2" to combustion chamber "Comb". The total differential head a pump must generate is a sum of static head difference and frictional head losses:

$$h_{tot} = h_{stat} + h_{fr}. \quad (3.32)$$

There is no height difference between fuel tank "T2" and combustion chamber "Comb". Fuel is stored at pressure of 1 atm. Frictional head loss is calculated based on fuel volume flow rate:

$$h_{fr} = k_{pipe} \cdot q_{v,fuel}^2, \quad (3.33)$$

where

- k_{pipe} is pipe friction coefficient $\left[\frac{mh^2}{l^2} \right]$
- $q_{v,fuel}^2$ is fuel volume flow rate

It is assumed that positive displacement pump volume flow rate depends only on pump speed and does not depend on pump head. Pump slippage is neglected. Pump volume flow rate with respect to pump speed is defined:

$$q_v = \frac{N}{N_{max}} q_{v,max}, \quad (3.34)$$

where

- N is pump speed
- N_{max} is maximum pump speed
- $q_{v,max}$ is maximum pump volume flow rate.

Pump head is limited to h_{max} . Pump speed is limited at given submarine depth such that pump total head does not exceed maximum head:

$$h_{stat} + k_{pipe} \left(\frac{N}{N_{max}} q_{v,max} \right)^2 \leq h_{max}. \quad (3.35)$$

Pump parameters are given in Excel Table 3.

3.2.7 Compressor

Part of flue gas at heat exchanger exit after mixing at mixing chamber "Mix" is returned to combustion chamber "Comb" by compressor "Comp". This flue gas return should ensure that flue gas stream "a" always exits combustion chamber at temperature below $\theta_{fg,max}$. Compressor "Comp" can provide any flue gas mass flow rate between minimum and maximum flow rate defined for that compressor type. It can be assumed that sufficient mass of flue gases is always available for return at mixing region "Mix".

Compressor is controlled with respect to fuel pump speed. Dependence between pump speed and return flue gas flow rate provided by the compressor is linear.

For fully defining correlation between compressor and pump, compressor loads L_{Comp} at two relative pump speed $N_{rel,1}$ and $N_{rel,2}$ have to be provided. Compressor load can have a value between zero and one and is defined as:

$$L_{Comp} = \frac{q_{m,ret} - q_{m,ret,min}}{q_{m,ret,max} - q_{m,ret,min}}, \quad (3.36)$$

where

- $q_{m,ret}$ is flue gas mass flow rate which compressor "Comp" returns to combustion chamber "Comb"
- $q_{m,ret,min}$ is minimal compressor mass flow rate
- $q_{m,ret,max}$ is maximal compressor mass flow rate

Compressor load at some relative pump speed N_{rel} is than:

$$L_{Comp} = L_{Comp,1} + \frac{L_{Comp,2} - L_{Comp,1}}{N_{rel,2} - N_{rel,1}} (N_{rel} - N_{rel,1}) \quad (3.37)$$

and is bounded between values 0 and 1.

Compressor parameters are given in [Excel Table 2](#).

3.2.8 Condensate pump

Condensate pump "P3" is used for return of condensed steam at low condensation pressure p_3 condenser "Cond" outlet to heat exchanger "HE" at high evaporation pressure p_4 . Specific enthalpy $h_4 = 359.83 \text{ kJ/kg}$ at pump outlet.

3.2.9 GUI

To help you chose the system parameters, once you choose the components the GUI (show on the figure 3.3) will be provided, so you can test the behavior of system you designed.

3.2.10 Constants

- $\theta_{fg,max} = 850^\circ C$
- $d_{pipe} = 20 \text{ mm}$
- $\delta_{pipe} = 2 \text{ mm}$
- $\lambda_{pipe} = 58 \text{ W/mK}$
- $Re_{crit} = 2300$
- $\alpha_{ev} = 3500 \frac{W}{m^2K}$
- $\alpha_{super} = 70 \frac{W}{m^2K}$
- $\theta_{fuel,in} = 10^\circ C$
- $\theta_{O_2,in} = 10^\circ C$

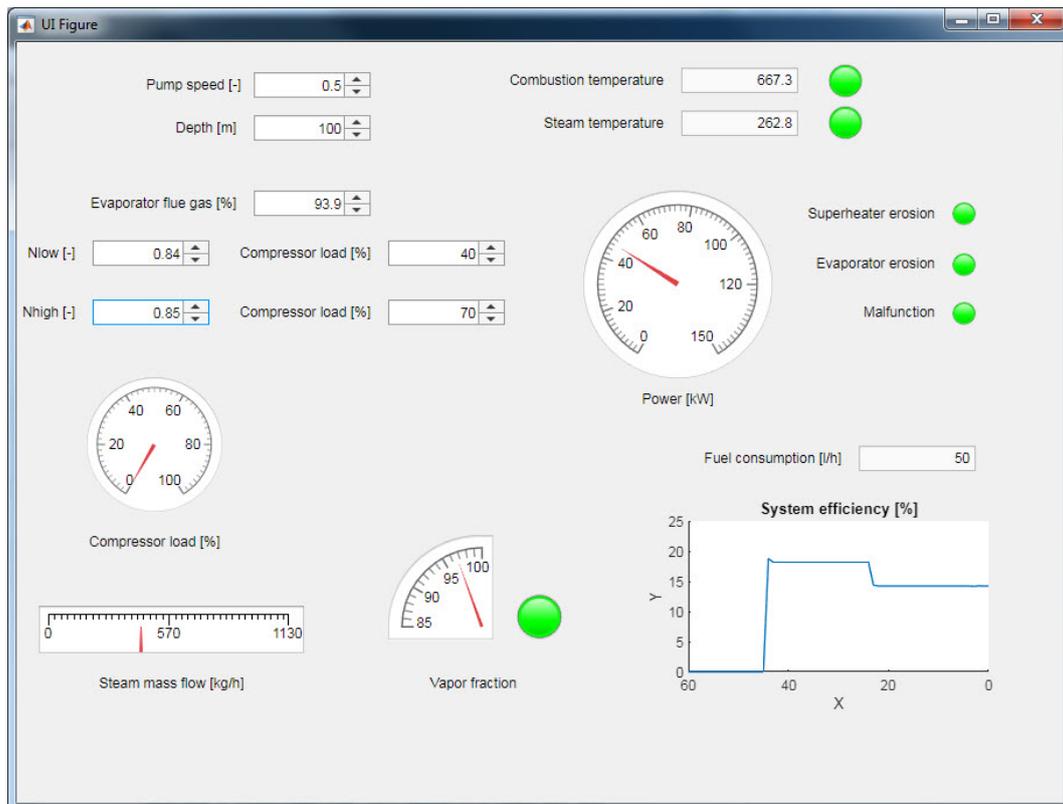


Figure 3.3: Day 2 gui

- $M_{\text{ethanol}} = 46 \frac{\text{kg}}{\text{kmol}}$
- $M_{\text{CO}_2} = 44 \frac{\text{kg}}{\text{kmol}}$
- $M_{\text{H}_2\text{O}} = 18 \frac{\text{kg}}{\text{kmol}}$
- $\Delta h_{\text{md}} = 1366940 \frac{\text{kJ}}{\text{kmol}}$
- $C_{mp, \text{C}_2\text{H}_6\text{O}} = 2.503 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$
- $\rho_{\text{sea water}} = 1000 \frac{\text{kg}}{\text{m}^3}$
- $\rho_{\text{ethanol}} = 789 \frac{\text{kg}}{\text{m}^3}$
- $\rho_{\text{oxygen, l}} = 1141 \frac{\text{kg}}{\text{m}^3}$

Fluid gas properties are given in Excel Table 4.

3.3 Beamforming system introduction

An underwater habitat connects wirelessly to a ship on the surface by means of ultrasonic hydrophones installed at the top of the habitat. In order to increase communications range, multiple hydrophones can be used to make a beamforming system. A flat rectangular area, 45 cm x 45 cm in dimension, is provisioned for this purpose. The area lies in the y-z plane of the reference coordinate system, as depicted in Figure 3.4.

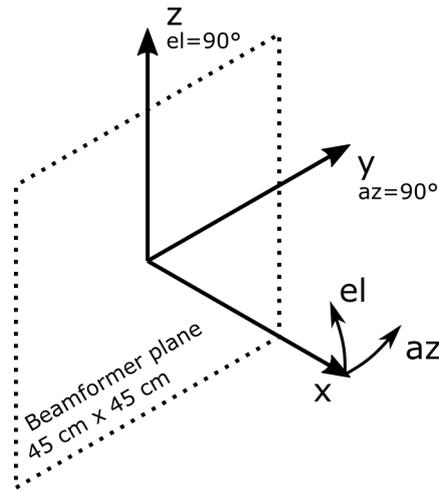


Figure 3.4: Reference coordinate system with available beamformer area

Hydrophone operates in frequency range of 20 kHz to 90 kHz. The communication link uses a carrier frequency of 30 kHz. Hydrophone has a cosine radiation pattern, described by expression

$$D(\phi, \theta) = \cos^2(\theta)$$

with ϕ being azimuth angle, and θ elevation angle. The radiation pattern is presented in the reference coordinate system in Figure 3.5.

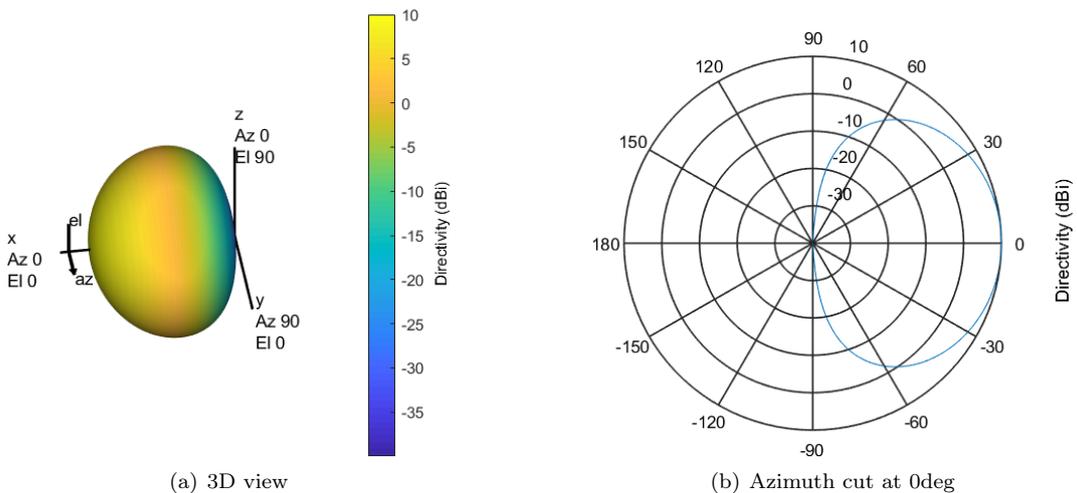


Figure 3.5: Radiation pattern of a hydrophone element

Physically, hydrophones are circular, 5 cm in diameter. All hydrophones in the beamforming system are installed with their radiation maximum pointing to zenith, i.e. perpendicular to sea surface, as described in Figure 3.5. At the other end, the ship is equipped with a single hydrophone mounted on ship's hull, and pointing at nadir, i.e. perpendicular to seabed.

Consider the signal narrowband. The ship is in the farfield of the beamforming system. Assume the communication link is being established in the Adriatic Sea, with average salinity of 38‰, and sea temperature of 20 °C.

3.3.1 Linear array

Design a single linear antenna array along the y -axis to achieve the best link between the habitat and the ship in four given scenarios.

Scenario 1 The ship is directly above the beamforming system.

Scenario 2 The ship is located along the longitudinal (y) axis of the beamforming system, at an azimuth of 30° .

Scenario 3 The ship is located along the longitudinal (y) axis of the beamforming system, at an azimuth of 60° .

Scenario 4 The ship is located along the longitudinal (y) axis of the beamforming system, at an azimuth of 70° .

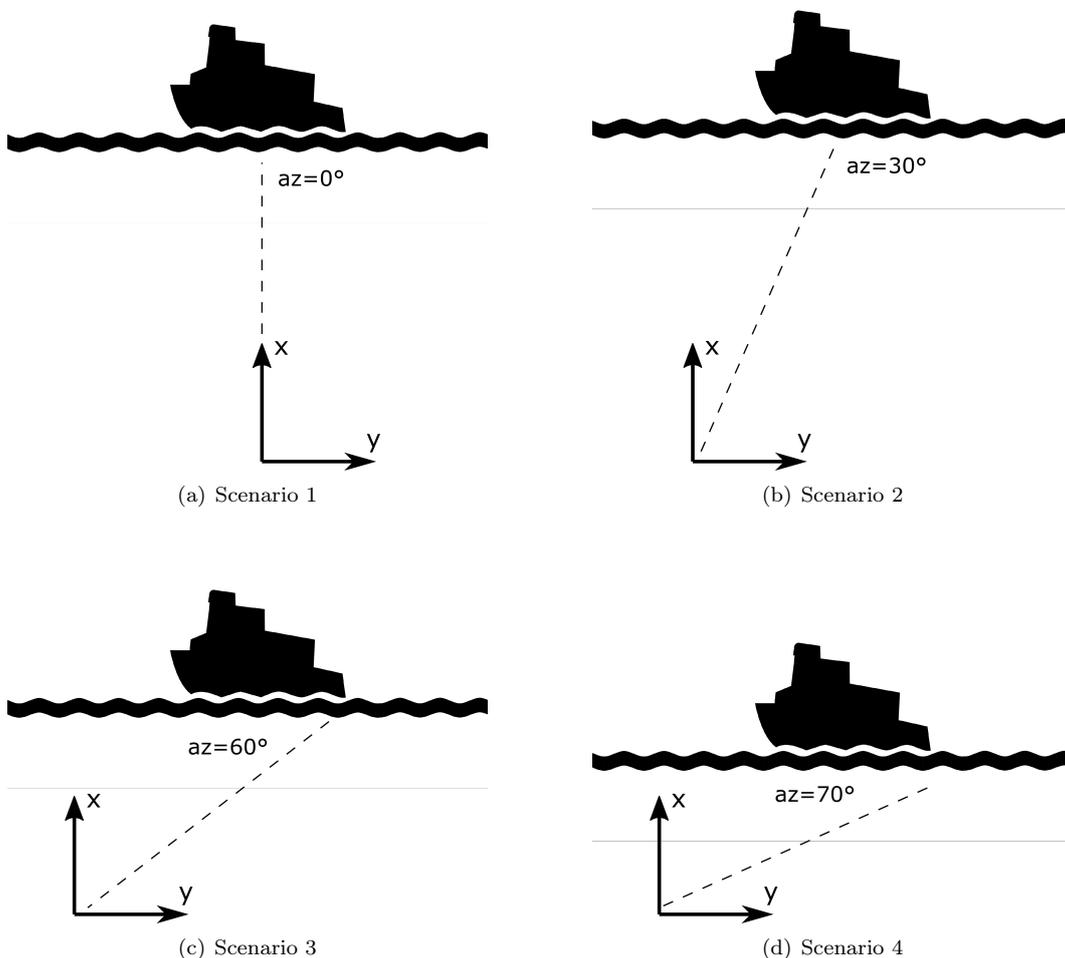


Figure 3.6: Scenarios for Task 1

A beamforming system is defined by y coordinates of each hydrophone element. Number of elements is arbitrary, given the limitations introduced in Introduction. The same beamforming system is used for all four scenarios. For each of the four scenarios, provide complex weights that are applied to each of the hydrophone elements to achieve optimal beamforming for the particular scenario.

Output data

elements1.csv

The file contains a one-dimensional array representing the position of each hydrophone

element along the y axis in metres.

scenarioX.csv e.g. *scenario1.csv*, ...

The file contains a one-dimensional array of complex numbers representing the weights applied to each hydrophone element. Weights are given for elements in the same order as they are listed in *elements1.csv*. Array length is equal to the number of elements in the beamforming system. All numbers are inside, or at the edge of the unit circle.

Complex numbers should be stored either in

- cartesian notation: $a+bi$, or
- polar notation: $P*\exp(Ri)$

Scoring

The beamforming system you designed is evaluated for each of the given scenarios. For the first three scenarios, points are awarded for the directivity the beamforming system achieves in the direction of the ship, after applying the given beamforming weights. If the ship is in the main lobe of the beamforming system, the number of awarded points is equal to

$$D_{\text{target}} - \Delta\phi$$

where D_{target} is the directivity in the direction of the ship in dBi, and $\Delta\phi$ the angular distance between the ship and the direction of beamformer's maximum directivity in degrees. If the ship is within the strongest sidelobe of the beamforming system, the number of awarded points is equal to

$$D_{\text{target}} - \frac{\Delta\phi}{10}$$

The ship is considered to be within a radiation lobe if it is within 6 dB of the considered radiation lobe's maximum radiation.

In scenario 4, the beamforming system is evaluated with the given beamforming weights, and its directivity compared to that of the same beamforming system with uniform excitation. The points are then awarded as

$$D_{\text{target,weighted}} - D_{\text{target,uniform}}$$

The highest number of points for this scenario is 20.

For all scenarios, the following rules apply: A beamforming system constructed with just one element is awarded no points. A beamforming system achieving negative directivity (in dBi) in the direction of the ship is awarded no points.

3.3.2 Planar array

You will now design a planar beamforming system, to enable beamforming toward a ship that is moving in both dimension along the sea surface. You are given a single scenario (*Scenario 5*) in which the ship is located at an azimuth angle of 45° and at elevation of 60° , as seen from the reference coordinate system.

Output data

elements2.csv

The file contains 2D coordinates of beamforming elements. One row of the file represents one beamforming element. The first column is the y-coordinate, and the second column is the z-coordinate.

scenario5.csv

The file contains a one-dimensional array of complex numbers representing the weights applied to each hydrophone element. Weights are given for elements in the same order as they are listed in *elements2.csv*. Array length is equal to the number of elements in the beamforming system. All numbers are inside, or at the edge of the unit circle.

Complex numbers should be stored either in

- cartesian notation: $a+bi$, or
- polar notation: $P*\exp(Ri)$

Scoring

The team will achieve points that correspond to directivity in dBi in the direction of the ship.

A beamforming system constructed with just one element is awarded no points. A beamforming system achieving negative directivity (in dBi) in the direction of the ship is awarded no points.

3.3.3 Evaluation and results

Evaluations are performed automatically, and will run continuously during the competition day. You can see the results of evaluation for all teams on a scoring board, and thus monitor how everyone progresses. The scoring board can be found on <https://engineering.stemgames.hr>.

You submit your output files to your team's Google Drive folder. After the simulation for your beamformer design is complete, you will find evaluator's log file on Google Drive.

The input files found on Google Drive at the end of the competition day will be taken as team's final solution. No changes will be accepted after that time.

At the end of the competition day, and after the final evaluations complete, the total number of points awarded to the team will be normalized to the best team. Hence, the best team will receive 10 points, and the points received by other teams will be linearly scaled to the best team.

Day 3

4.1 Introduction

Hello contestants!

Today you will continue the work on the communication system and on the next stage of the power system - the power generator connected to the steam turbine.

No modern system can work without the reliable communication with the outside world. Today through the solving of the SDR (Software Defined Radio) task you will get the feeling of what is needed to create a reliable communication system. Once the signal has been directed using the beamforming, you need to receive the data being transmitted, demodulate the data and check for any errors.

In most submarines, the main turbine isn't connected directly to the shaft, but rather to the electric generator, which charges the batteries. Batteries power the life support, air condition, lights, the propeller motor and all the other submarine subsystems. In continuation of the yesterdays design of the steam turbine, you will have to design an appropriate synchronous generator.

4.2 Software Defined Radio

4.2.1 Task 1

An underwater habitat controls a remotely-operated submarine by sending the coordinates that the submarine has to traverse in sequence. The information is modulated on top of an ultrasonic carrier, and then sent and received by a hydrophone system.

The 3-dimensional coordinates are organized into triplets, as `xxx.xxx,yyy.yyy,zzz.zzz;`. Each digit and separating characters (", " and ";") are encoded as an 8-bit ASCII character. Triplets are concatenated and sent sequentially. This datastream is the input to the modulating system of the transmitter.

The transmitter first organizes the input stream into packets. Each packet consists of a preamble, header, data, CRC-16 hash, and a postamble. The frame structure is illustrated in Figure 4.1.

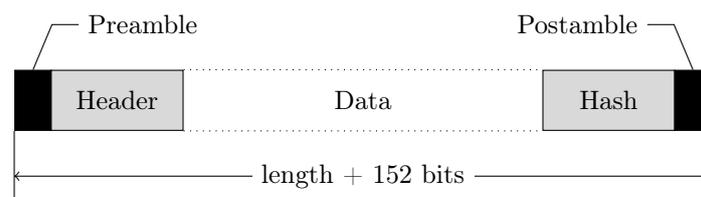


Figure 4.1: Packet structure

Preamble is a predefined 64-bit sequence `0xa5a5a5a5a5a5a5a5`. Postamble is a bitwise-inverse of the preamble. Header is an 8-bit word containing byte-length of the data section in the packet. The shortest size of the data section is 64 bits, while the largest is 248 bits. The data section is always byte-aligned; i.e. its length is always a multiple of 8 bits.

All the words in the packets are stored in big endian notation. The packets are sent further through the transmitter chain sequentially, without a guard interval.

The binary sequence of the generated packets is brought to a QPSK modulator. Its constellation is represented by Figure 4.2.

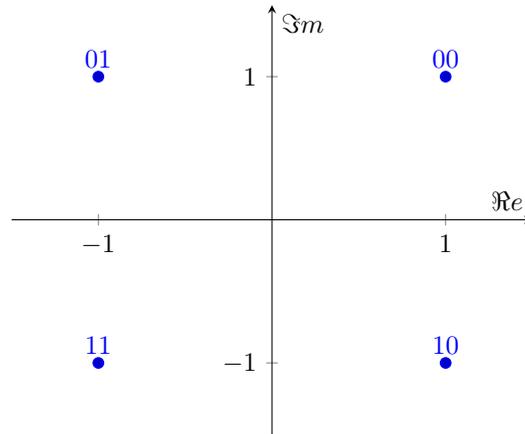


Figure 4.2: QPSK modulator constellation

The QPSK-modulated symbols are transposed to carrier frequency $f_c = 36$ kHz and transmitted by a hydrophone. Transmitter data-rate is 9.6 kbaud. At the receiving end, the receiver aboard a submarine is depicted by a block diagram in Figure 4.3.

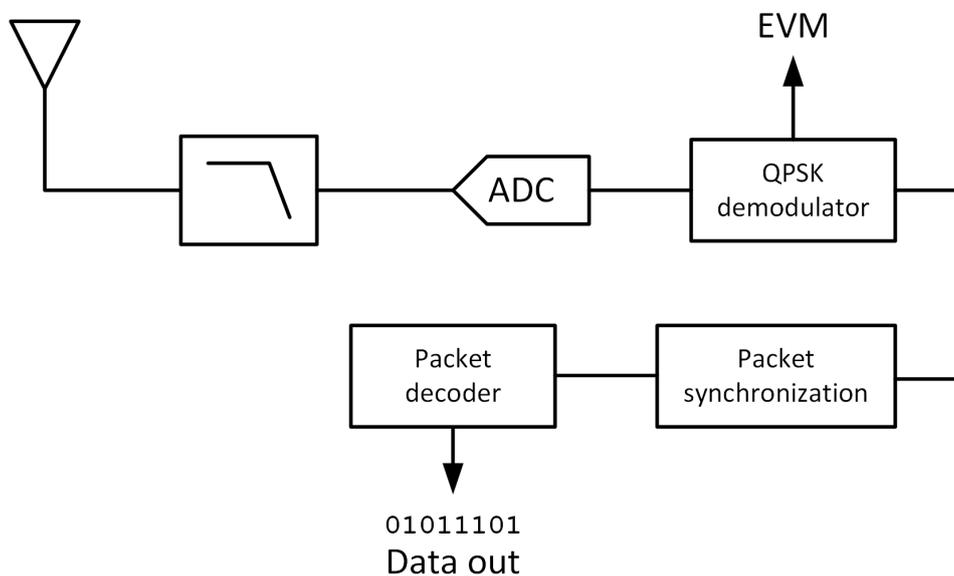


Figure 4.3: Receiver diagram in Task 1

The ADC of the receiving hydrophone operates at a sampling frequency of 192 kSps. An ideal low-pass filter has a cut-off frequency of 96 kHz.

You are required to implement the digital processing system of the receiver, to demodulate and decode information from the received ultrasonic signal.

Input data

The `single_carrier.raw` file is given. It contains the digitized signal from the ADC, recorded in 16-bit 2's complement format.

Implementation

Your solution is a C or C++ code implementing the receiver's digital processing chain. Your solution consists of two files:

radio.c / cpp Implements all the routines described further in the text.

main.c / cpp Loads the input data, calls the routines from `radio.c / cpp`, and outputs decoded data to stdout in the original format.

Your `radio.c / cpp` file must implement the following set of functions:

complex *frequency_shift(double *input, double fc, double fs, int N)

Transposes the signal provided in `input` from centre frequency `fc` to baseband. `N` is the length of the data stream, expressed as a number of double words. `fs` is the sampling frequency.

double qpsk_demodulator(complex symbol, double constellation_offset, char *decoded_symbol)

Decodes a baseband QPSK symbol `symbol`, and stores its value to an 8-bit word `decoded_symbol`. The function outputs the EVM of the symbol.

char *bitstream_to_bytestream(char *bitstream, int length)

Converts length 8-bits words, as output by the `bitstream_to_bytestream` function, into a bytestream. Parameter `length` is the length of the bitstream array, while the length of the output array is equal to `length/4`. A pointer to the beginning of the bytestream is returned.

void frame_sync(char **bytestream, int length)

Moves the pointer `*bytestream` to the beginning of the first detected frame. `length` is the length of the bytestream.

int frame_decoder(char *bytestream, char **data)

Decodes the data from a single frame that starts at the pointer `*bytestream`. The decoded data should be stored to `*data`. The return value is the length of processed data (frame length).

You are provided with some helper files:

api.h

An API containing some types, functions and constants you may find useful.

api.c

The compiled API described in `api.h`.

Evaluation

You have access to an evaluation server to which you can upload your source files. The server will execute your code and verify the functionality of each function implemented in your `radio.c / cpp` file. The server functionality will further be described in a document that you will receive at the start of the competition day.

4.2.2 Task 2

Along the submarine's trajectory information, the habitat and the submarine exchange location data on debris scattered around the sea. This data is transmitted in a separate data stream from the trajectory coordinates, and it has the same triplet format as the data from Task 1. Also, the data is packaged in the same manner as in Task 1. The resulting bitstream is then spread into 4 QPSK subcarriers, as depicted in Figure 4.4.

The obtained QPSK carriers are multiplexed into OFDM that consists of a total of 9 subcarriers. These are organized as depicted by DFT spectrum in Figure 4.5.

Subcarrier spacing is $\Delta f = 1500$ Hz. The graph in Figure 4.5 is centred to frequency $f_c = 36$ kHz, corresponding to the central frequency of the OFDM carrier. The subcarrier

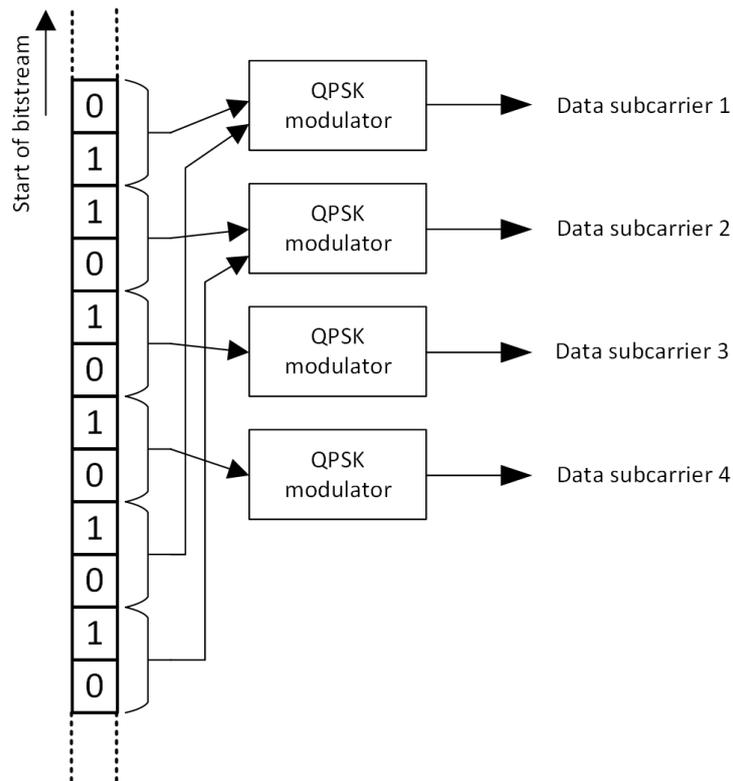


Figure 4.4: Bitstream spreading mechanism

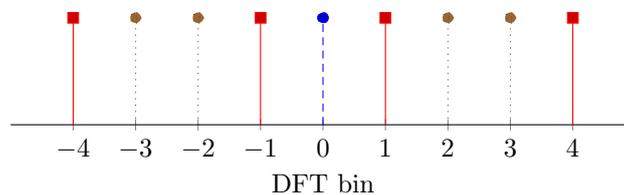


Figure 4.5: OFDM carrier DFT spectrum

at bin 0, depicted by a dashed line, contains trajectory coordinate stream from Task 1. Subcarriers depicted by dotted lines contain the data stream added for this task. Subcarriers depicted by a solid line are pilots. OFDM symbols have no cyclic prefix.

The receiver code from Task 1 has to be modified to work with an OFDM carrier, and decode the additional data stream. Block diagram of the receiver is presented in Figure 4.6.

Input data

The `ofdm_carrier.raw` file is given. It contains the digitized signal from the ADC, recorded in 16-bit 2's complement format.

Implementation

You should update your `radio.c / cpp` and `main.c / cpp` to implement the new features required for Task 2. Your `radio.c / cpp` file should implement the following additional functions:

```
double *ofdm_demodulator(complex *spectrum, int *carrier_idx, int carrier_no,
char **data)
```

Takes the spectrum of a single OFDM symbol from `*spectrum`, and demultiplexes the subcarriers containing the additional data stream. The demodulated QPSK symbols from these subcarriers are stored in a bitstream array that starts at `*data`. Demodulated QPSK symbols from each subcarrier are stored in their own chars, to be used as input to the `bitstream_to_bytestream` function. The input signal is in baseband in the original

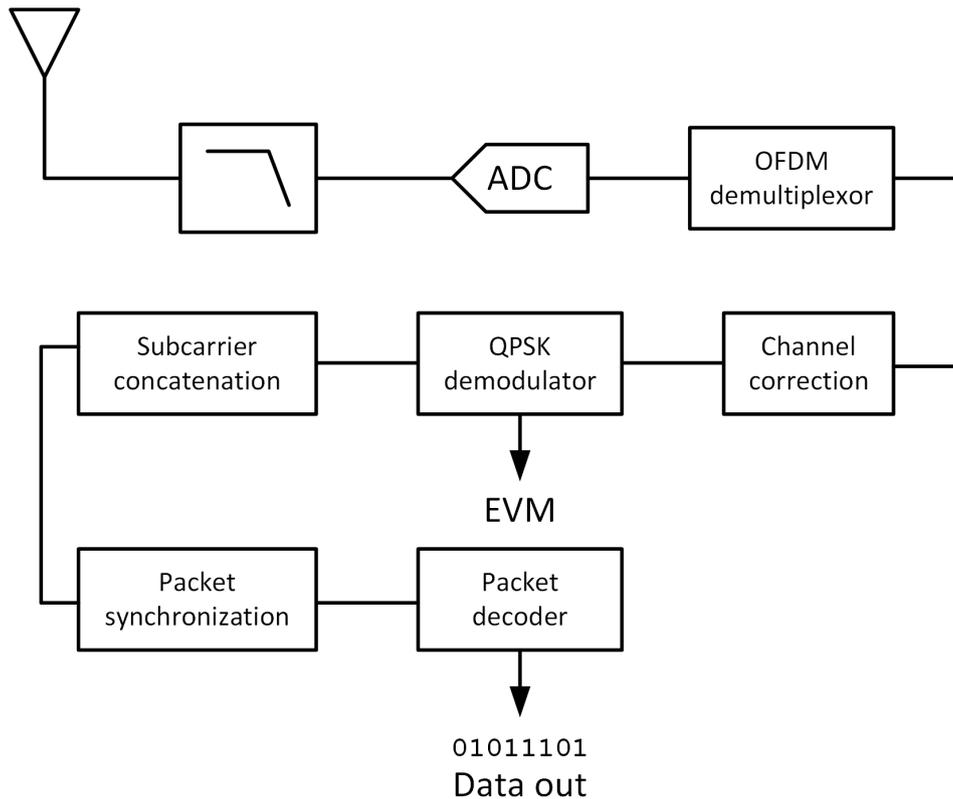


Figure 4.6: Receiver diagram in Task 2

sample rate. `carrier_idx` is a list of DFT bins that contain the additional data stream. `carrier_no` is the length of `carrier_idx` array.

Evaluation

OFDM-capable `radio.c / cpp` file is submitted at the end of the competition day.

4.2.3 Task 3

An algorithm for calculating the CRC-16 hash of an input stream should be added to solutions for both tasks. CRC-16 verification should first be implemented as a separate function, and then integrated into the receiver chain. The modification is presented in Figure 4.7.

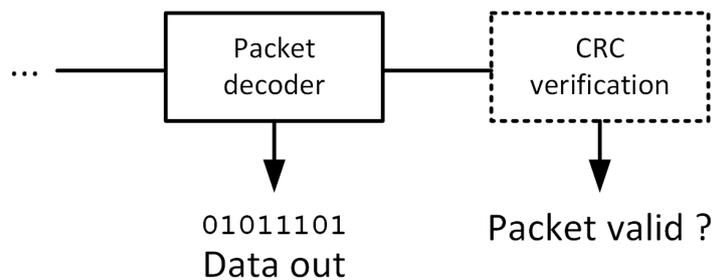


Figure 4.7: CRC check in receivers

The CRC-16 hash in data frames is calculated using the CRC-CCITT algorithm, with an initial register state `0xffff`.

Implementation

Your `radio.c` / `cpp` code must implement the following additional functions:

`char crc16_check(char* bitstream, int length)`

Returns CRC-16 hash of the given `bitstream`, of length `length`.

`int frame_decoder_valid(char* bytestream, char data, bool *valid)`**

Decodes the data from a single frame that starts at the pointer `*bytestream`. The decoded data should be stored to `*data`. The output flag `*valid` denotes if the decoded frame has a valid CRC-16 checksum. The return value is the length of processed data (frame length).

Evaluation

A `radio.c` / `cpp` capable of performing error detection is submitted at the end of the competition day.

4.2.4 Documentation

Provide documentation that describes your solution for the receiving chain. Back your implementation by describing the mathematical background of your processing chain. Document the datasets you used to evaluate your solution.

The documentation will not be graded, but it can help mentors in understanding your approach and validating the theory behind your solution.

4.3 Synchronous machine design

4.3.1 Introduction

Your submarine needs electric power to drive the main propeller shaft and to operate all the equipment on board. The main supply of the electric power on your submarine is a synchronous generator. The generator rotor is fitted on the same shaft as the steam turbine. The generator converts the mechanical power from the steam turbine into electrical energy which is supplied to each load on the submarine. Generators are typically purchased based on the requirements of a specific application. In this task you will be designing a three-phase synchronous generator for your submarine. Nominal values of the synchronous generator are given as:

Table 4.1: Nominal values of the generator

| | | | |
|----------------------|--|---------------------|----------|
| No. of Phases | 3 | Frequency | 50 Hz |
| Voltage | 400 V,  | Speed | 3000 rpm |
| Power rating | 100 kVA | Power factor | 80 % |

4.3.2 Calculation of the machine parameters

Synchronous generator design is not a simple task and to make it easier for you only a limited number of parameters needs to be determined.

The main dimensions of the generator that you need to calculate are:

- the stator bore diameter,
- the rotor diameter,

All of the machine main dimensions must be calculated in meters.

Next, you have to determine:

- the number of conductors in the stator slots (round to the first higher integer),
- the number of field winding turns (integer).

Lastly, the design of the generator is finished with the calculation of the synchronous reactance in p.u.

Generators used in applications with steam turbines (high-speed applications) are ones with a cylindrical (round) rotor. The rotor body of the generator is typically a solid piece of steel for reasons of strength, given the high rotational speeds to which the rotor is subjected. The rotor diameter is sized to operate at near the stress limit of the steel alloy. The maximum allowable peripheral speed of the generator is 80 m/s which means the machine must be capable of sustaining 70 % overspeed.

Windings located on the rotor of the generator are called field (excitation) windings. Field windings are supplied with direct current. The external source used to provide DC current is commonly referred to as an exciter. At the no-load condition, the exciter supplies field windings with DC current equal to 28 A which is required to create a field current linkage of 1904 A. In order to describe the magnetic circuit of the machine and the required field current linkage, Ampere's law may be used. The current linkage produces magnetic flux density sinusoidally distributed along the pole. During half of the period T the flux density wave travels one stator pole pitch. The maximum value of the magnetic flux density in the air gap is 0,8 T and the length of the air gap is constant. Iron's magnetic permeability can be assumed to be infinite in comparison with the magnetic permeability of air. Stator windings or armature windings are full-pitch one-layer windings embedded in 36 slots. Stator length is 0.5 m. A synchronous generator can be represented by a simple equivalent circuit as shown in figure 4.8. Phase voltage measured on the output terminals of the generator is lower than the induced phase voltage due to the voltage drop on the stator impedance. The synchronous reactance prevails in the stator impedance which means that the stator resistance can be neglected when calculating the synchronous reactance. In nominal conditions (nominal

voltage, power factor and load) the angle between the terminal voltage and the induced voltage is equal to 25.07° . In order to determine the characteristics of the synchronous

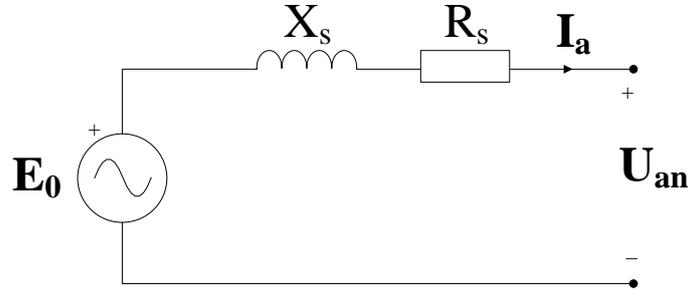


Figure 4.8: Synchronous machine equivalent circuit

generator standardized tests must be carried out. The simplest method by which this is achieved are the open-circuit and the short-circuit tests. Typical open-circuit and short-circuit curves are shown in figure 4.9. During the open-circuit the field winding is supplied with the nominal field current I_{fn} and the line voltage measured on the generator terminals is equal to 680.235 V. In case when the field current is equal to $I_{f0} = 28$ A, the voltage measured at the generator terminals will be equal to the nominal voltage. During the short-circuit test when the field winding current equals to I_{f0} the measured stator current will be 92.524 A.

The per-unit system is widely used within the analysis of electrical machines. Per-unit values are obtained by dividing each parameter by a base value. For this task the base values are defined with:

- peak value of the rated stator phase voltage,
- rated apparent power,
- rated angular frequency,
- peak value of the rated stator phase current.

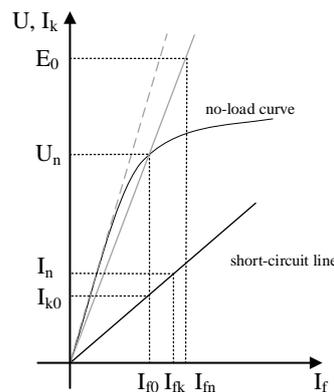


Figure 4.9: Open-circuit and short-circuit curves

4.3.3 Solution format and grading scheme

Your solution must be submitted as a .csv format document with only 2 rows. File name must be `machineParameters.csv`. The first row must consist of the required parameter names and the second row of numerical values that you calculated for each parameter. Column names must be marked as follows (columns should be in exactly this order):

- stator bore diameter **Ds**,
- rotor diameter **Dr**,
- air gap length **delta**,
- number of conductors in the stator slots **z**,
- number of field winding turns **Nf**,
- synchronous reactance in p.u **Xd**.

This task is graded up to 20 points. 3 points are given for each correctly calculated parameter and 2 points are given for the documentation. The documentation is submitted at the end of the day. The documentation must include your calculations along with some short comments explaining the equations. You can choose the format in which the documentation will be submitted (.c script, .m script, hand written equations).

4.4 Submarine driving

Finally, the last task of this year's Engineering arena is here! All your calculations in the past 3 days lead you up to this! You have to drive your submarine and transport people and goods to underwater habitats.

A map of the sea bottom is shown in figure 4.10. Your task is to visit all 3 habitats and return to the starting position. To visit a habitat you need to be within 3 meters of the habitat for 60 seconds. Leaving that range resets the timer.

Green dot is the start position of the submarine (0, 0). Every other colored dot on map is one habitat you have to visit. Blue line represents bottom of the sea so you have to be careful and not drive your submarine into it. We also provide you with the function used to generate the bottom : $0.01 * (500 * \sin(0.005 * X) - X) - 50$. Y level zero is the surface of the sea.

Colliding with the sea bottom is instant fail.

Table 4.2: Habitats and coordinates

| Habitat | X[m] | Y[m] |
|---------|------|--------|
| Red | 1039 | -64.82 |
| Yellow | 2708 | -72.95 |
| Purple | 3535 | -89.96 |

The following dimensions are given:

- $L = 15$ m
- $D_{OUT} = 3.4$ m
- $D_{IN} = 3$ m
- $m = 104.419$ t
- $ballast\ volume = 30\ m^3$
- $ballast\ equilibrium = 50\%$
- $ballast\ fill\ speed = 100\ l/s$

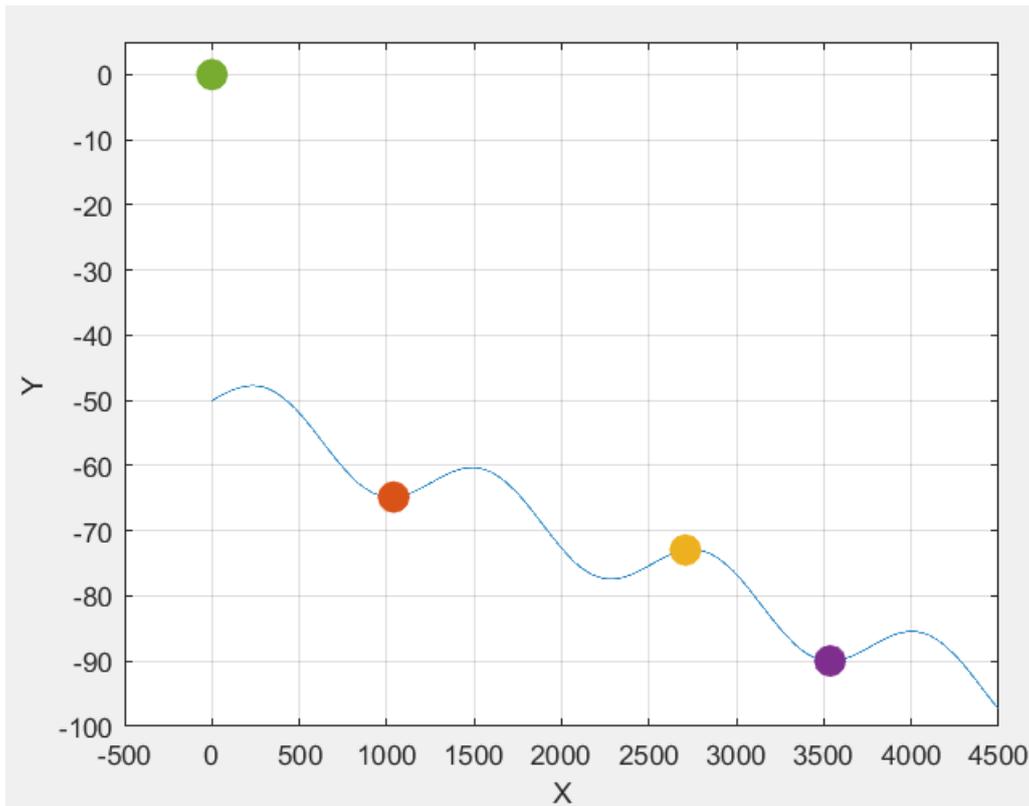


Figure 4.10: Map of the sea

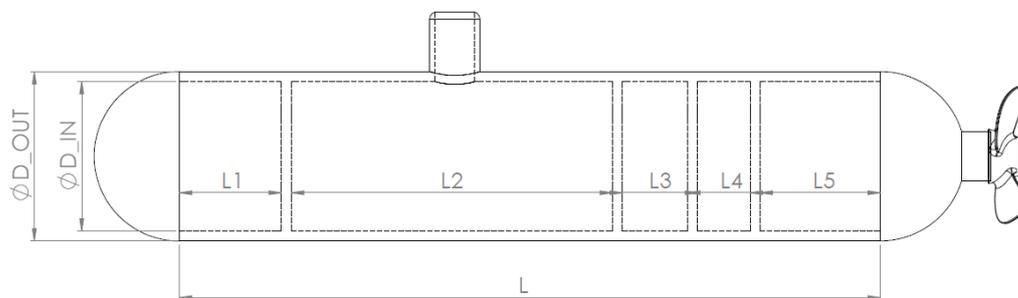


Figure 4.11: Submarine dimensions

Driving references are in this order : Red, Yellow, Purple.

To help you in designing your driving function, GUI will be provided. GUI will allow you to change the submarine inputs and see how the submarine behaves. Example of the info you get from the GUI is provided on the figure 4.12.

Based on that, you have to design a regulator as a matlab function with prototype given in your task's folder.

Function output:

Fuel percentage - 0.35, 1 - Desired % of fuel pump speed

Angle - $-7, 7$ - In degrees, vector of the output thrust

Target balast fill - 0, 1 - Desired balast fill %, the tank fills and empties with the *ballast fill speed*

Motor stop - If this value is 0, the propulsion motor is shut down

Reverse - If this value is negative, propulsion motor is reversed

Function input:

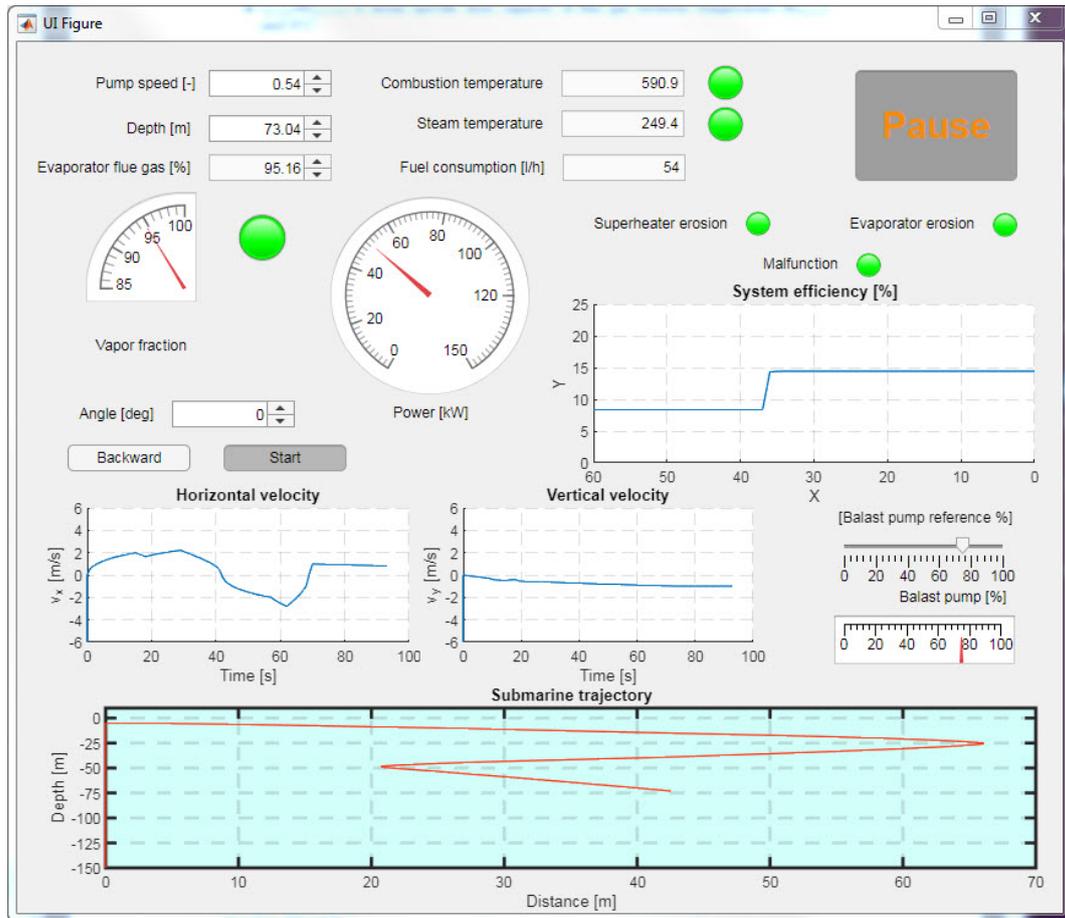


Figure 4.12: Day 3 GUI

pointIndex - Index of habitat that is current reference point([1, 2, 3] for [Red, Yellow, Purple], respectively)

vx, vy - X and Y speeds

sx, sy - X and Y positions

We will grade you **only by time** to perform whole trip.