STEM Games 2019
Engineering Arena

LET THERE BE LIGHT

a problem by

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1 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 Tasks

The system for which you have to design a controller is the crane shown in the Figure 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. Masses of each part of the crane are listed in Table 1. **For the sake of simplicity and overall system dynamics, load has the mass** $m_{load} = 800.59kg$.

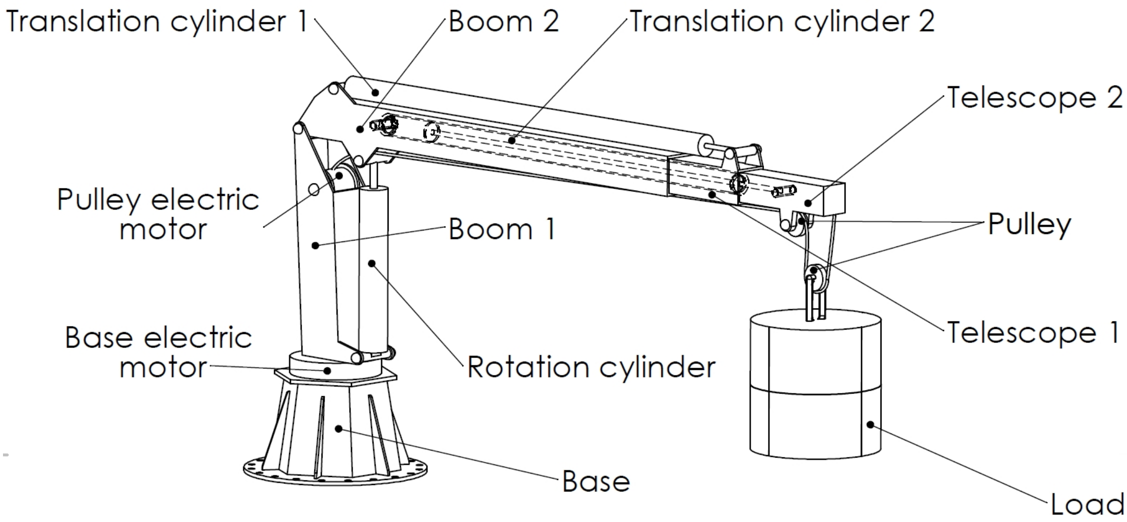

Figure 1: Crane configuration, isometry.

Table 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 Hydraulics system

Part of the crane is actuated using hydraulic system. The system, as we designed it, is shown in Figure 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.

2.2 Kinematics

Crane configuration and dimensions are shown in Figure 3, Figure 4 and Figure 5. Figure 6 shows cylinder configuration with corresponding dimensions given in Table 3. Load is shown in Figure 7. **Crane configuration has been sketched for** $q_1 = 0°$, $d_1 = 194mm$, $d_2 = 369mm$, $d_3 = 437.22mm$ **and** $q_2 = 0°$. **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.

Table 2: Actuator position limits

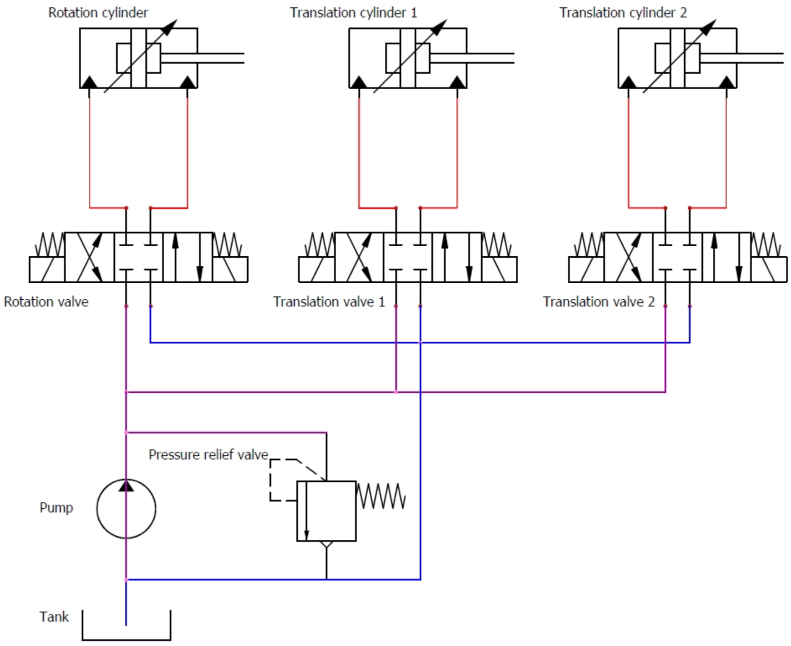

Figure 2: Hydraulic system schematics.

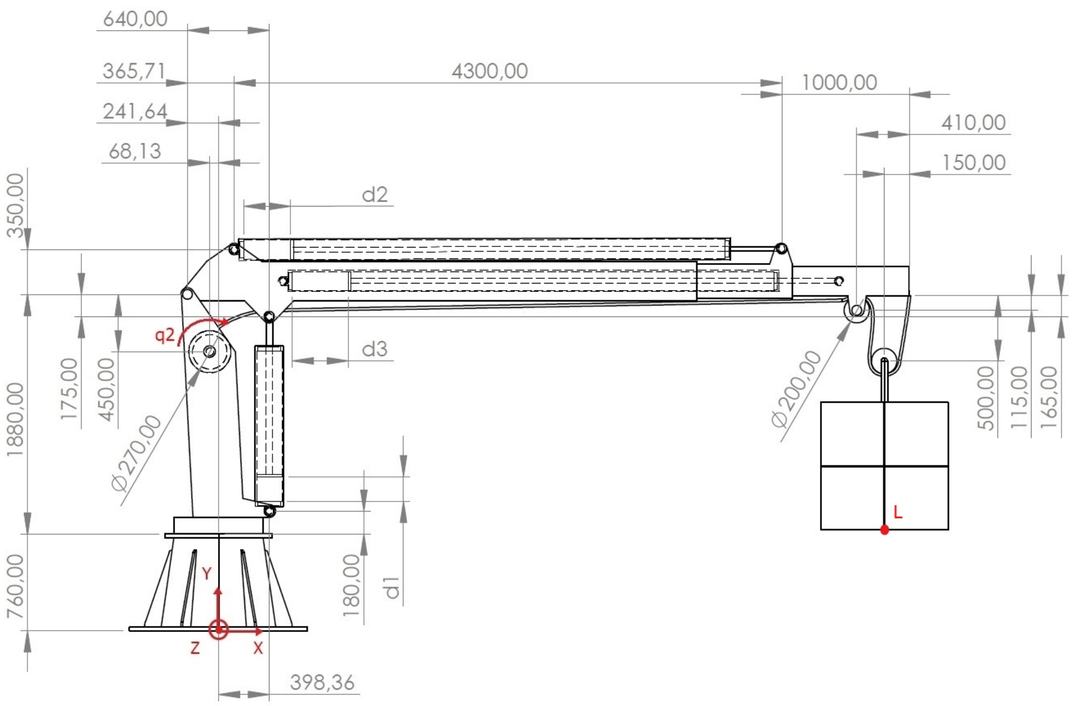

Figure 3: Crane configuration, side view.

Variable	q_1[°]	d_1[m]	d_2[m]	d_3[m]	q_2[°]
Minimum value	×	0	0	0	0
Maximum value	×	0.8	3.5	3.5	20000

Table 3: Cylinder dimensions

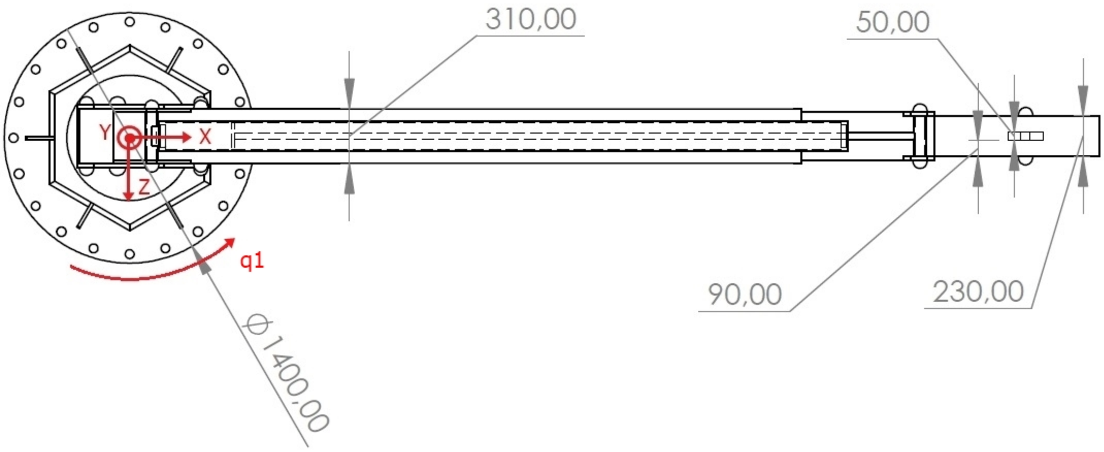

Figure 4: Crane configuration, top view.

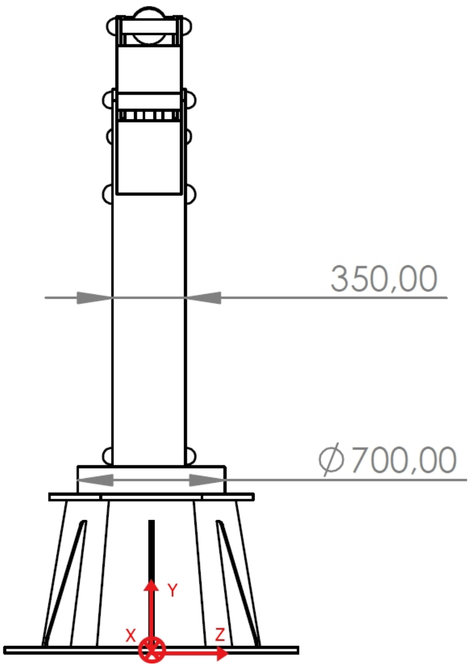

Figure 5: Crane configuration, back view.

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

2.2.1 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 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 4: Direct kinematics configurations

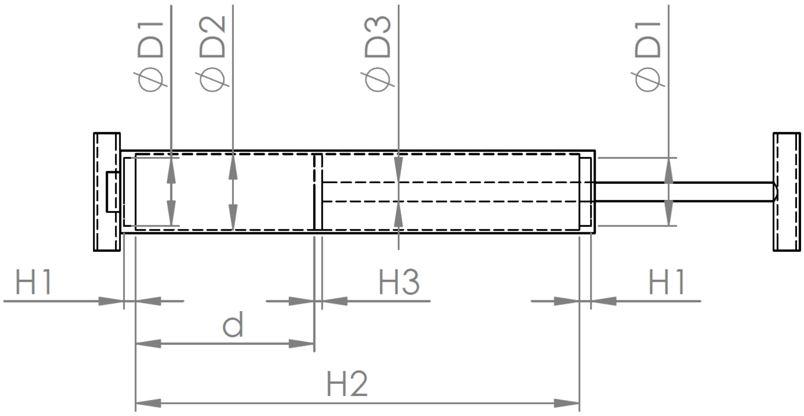

Figure 6: Cylinder configuration with dimensions.

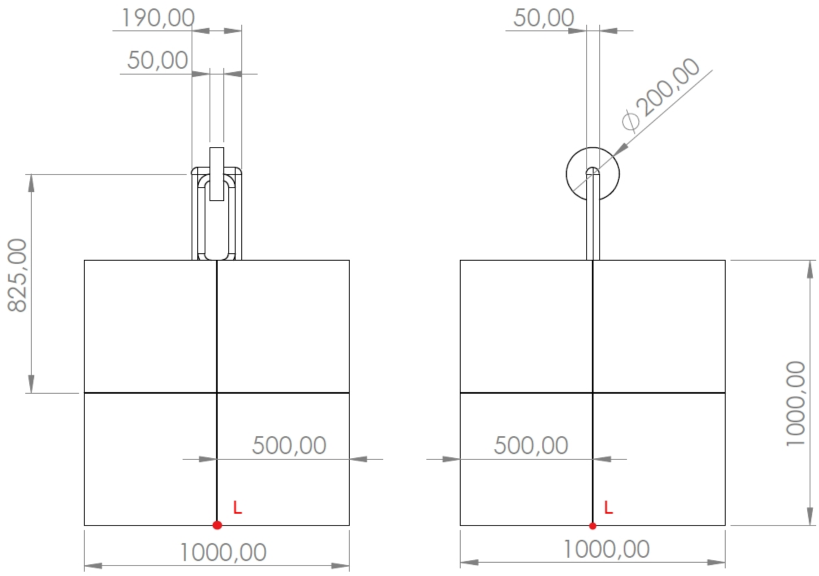

Figure 7: Load

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.

2.2.2 Inverse

Next step is to be able to determine kinematic configuration in opposite direction. Based on load positions specified in Table 2.3, 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 2.3.

Table 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.

2.3 Model identification

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), 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 7. In task's *readme* file you can find a way how to test your input signals and submit your results.

Table 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 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.

2.4 Crane driving

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 2.3 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 8.

Table 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:

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

$$D_i = \begin{cases} \sum_{t=T_{i-1}}^{T_i} ||L(t) - P_i||, & P_i \text{ reached,} \\ \\ 10000, & P_i \text{ not reached,} \end{cases} \tag{2}$$

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.

3 DC voltage power supply

3.1 Introduction

For fully functional operation, submarine 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. 10. 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 each task you have to ensure that the values specified in the table correspond to the values which will be measured in simulation.

Table 9: Device specifications

PARAMETER	TEST CONDITIONS	VALUE	UNIT
Input voltage (U_{in})		330	Vpp
Output voltage (U_{out})	$I_{out} = 1$ A	10 ($\pm$5) %	V
Output current (I_{out})	$U_{in} = 330$ Vpp	1.0	A
Ripple rejection	(12.8 kHz)	78	dB

Table 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	MΩ
R_4	Resistance	470	kΩ
R_L	Resistance	10	Ω
Q_1	U_{pn}	0.6	V
C_1	Capacitance	10	mF

3.2 Finding the proper choice of components

As it can be seen from the table 10, some components are not determined. In this subtask you need to specify resistor R_1 and diode D_2. Additionally, you have to determine positions of the negative and the positive input of the amplifier A_1. Based on the regulators operating values provided with table 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. 8,
- 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 two DigiKey part numbers for resistor and diode, respectively.

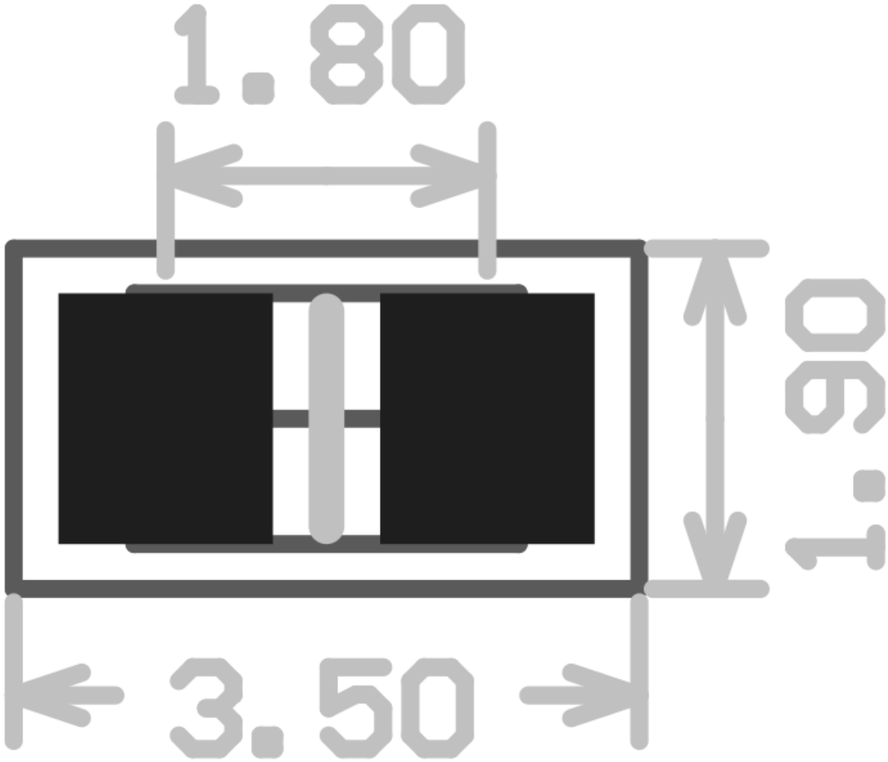

Figure 8: Component footprint with dimension in millimeters

3.3 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 12.8 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. 8,
- Q factor has to be equal $\frac{\sqrt{2}}{2}$ for $R_L = 10\ \Omega$.

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 two DigiKey part numbers for inductor and capacitor, respectively.

3.4 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. 9. 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:

$$f_1(t) = \lambda_1 e^{-\lambda_1 t} \tag{3}$$

and for the second regulator:

$$f_2(t) = \lambda_2 e^{-\lambda_2 t} \tag{4}$$

Your task is to determine probability density function $f_S(t)$ which gives the probability of failure in system described with Fig. 9. 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 $T_{sf} = T_{1f} + T_{2f}$.

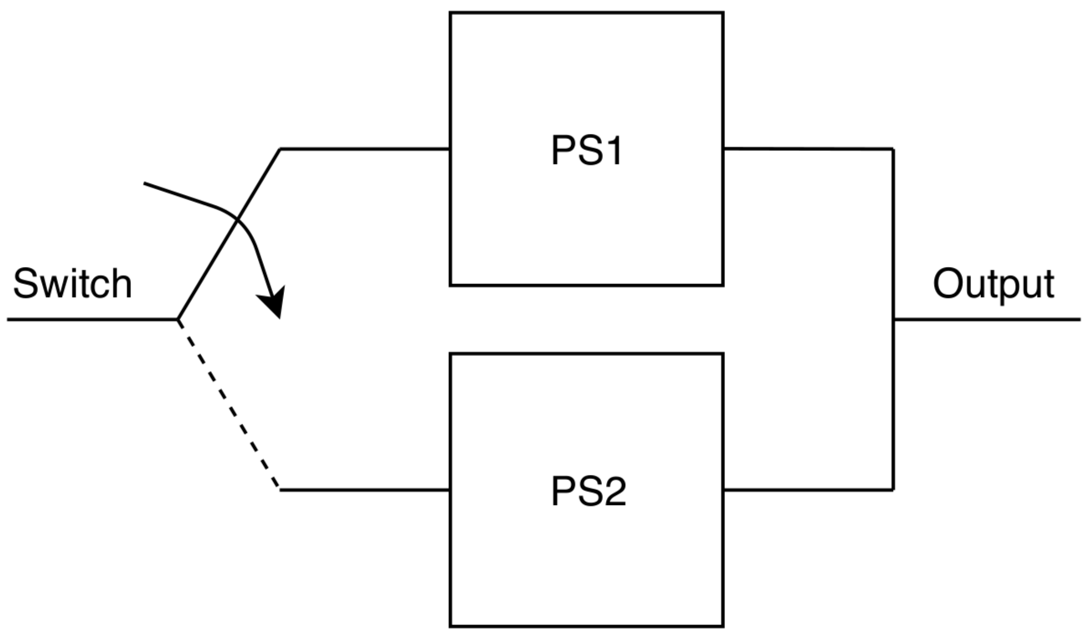

Figure 9: Standby system configuration

3.5 Solution format

Solution for each task is a plain text document containing requested data. For the tasks 3.2 and 3.3 text documents need to have two rows. One component part number in each row. Only one row is needed for the task 3.4 (requested probability). Name the files `task1.txt`, `task2.txt`, `task3.txt` and put them in the appropriate Google Drive folder.

Additionally, for the task 3.4 you have to provide documentation which has to contain derivation of $f_S(t)$.

3.6 Grading scheme

Tasks are graded in the following manner:

- tasks 3.2 and 3.3 - up to **10 pts**, up to **5 pts** for each component.
- task 3.4 - up to **10 pts** - **5 pts** for the correct probability and up to **5 pts** for correct documentation.

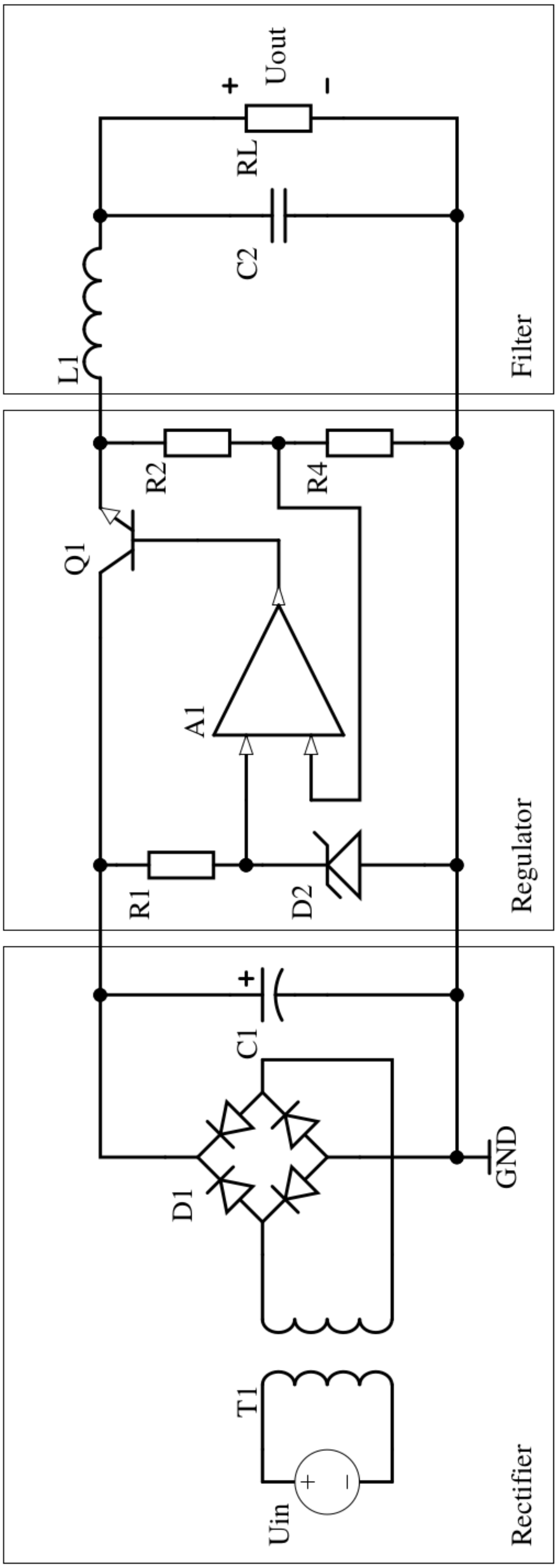

Figure 10: DC voltage power supply schematic