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Development of a mechatronic solution for a new type of heat engine

The selection of relevant electronic components and control system for the mechatronics for the lab model of the new heat engine the Green Revolution Energy Converter

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Foreword

A short summary of the three authors different individual contribution to the project is presented below. A column with comments about who

Acitvity	**Oskar**	**Lisa**	**Max**	**Comment**
Problem analysis and planning	33 %	33%	33%	Collective planning phase.
Background research	33%	33%	33%	Collective research
Implementation and carrying through the work:	-	-	-	-
Component research	40 %	20 %	40 %	Oskar and Max had the main responsibility
Write code	50%	0%	50%	Oskar and Max teamed up
Design wiring diagram	0%	100 %	0 %	Lisa had the responsibility
Soldering	50%	30%	20%	Oskar did most of the soldering
Mock-up and testing	35%	30%	35%	
Writing the report:	-	-	-	-
Introduction	33%	33%	33%	Equal contribution
Theory	33%	33%	33%	Equal contribution
Method	33%	33%	33%	Equal contribution
Results	25%	40%	35%	
Discussion and conclusion	50 %	25%	25%	Oskar had the main responsibility
Reference handling	10%	45%	45%	

Abstract

The Green Revolutionary Energy Converter (GREC) is a new heat engine based on the theory from the ideal process of the Carnot cycle. The inventor is Nils Karlberg and his company nilsinside AB, and there have been two previous projects regarding the GREC motor at LiU. The GREC motor consists of a rotating shutter which with the help of an electric motor rotates a fluid that is being heated on one side and cooled down on the opposite side. Due to this temperature difference there also occurs a pressure difference in the fluid between the warm and cold side, from which energy theoretically could be extracted.

The purpose is to design and implement an electric system capable of rotating the shutter as well as measuring desired data from inside the GREC, such as pressure and position. Research questions were formulated to investigate the influence of the GREC for different choices of components. For this an electric motor and relevant sensors are to be chosen from a specific set of requirements, as well as formulating code with some control system built in and designing a wiring diagram. Carrying out this method resulted in components being chosen, code without a control system was implemented, a wiring diagram was designed.

Contents

Nomenclature

Nomenclature	
Acronym	Word
WGV	Work generating volume
RS	Rotating shutter
$GREC$	Green Revolution Energy Converter
RPM	Revolution Per Minute

List of Variables		
Variable	Description	Unit
F	Force on RS	[N]
b	Width of the WGV	[m]
L	The circumference of the RS	[m]
A	Area of the side that "hits" the air	[m^2]
U_∞, V	Speed of the RS	[m/s]
ρ	The density of air	[kg/m^3]

List of Dimensionless variables		
Variable	Word	Unit
Re	Reynolds Number	NaN
C_D	Drag coefficient	NaN

1 Introduction

In this section, the project will be introduced with the background, previous work and the budget for the GREC project.

1.1 Background

Today the world is facing big problems regarding emissions of greenhouse gases which increases the global warming. A lot of existing large systems emits waste heat that our current technology cannot convert to energy. The GREC (Green Revolution Energy Converter) is a new concept of a thermal motor which aims to generate energy from energy due to heat loss.

1.1.1 Company

nilsinside AB is a company focusing on research and development of sustainable energy recovery based in Sweden. Their main focus is on development of the GREC engine, an invention by their founder Nils Karlberg to which they hold multiple patents. This technology aims to reduce energy loss due to excess heat from other processes. Technology Readiness Level (TRL) is a system which defines at what state a technology is at on a scale between 1 and 9. A lower rating indicates a more research level project while a higher rating indicates a technology that is closer to being sold to customers. At this point, the GREC has a rating between 3 and 4. Level 3 meaning that the GREC has research behind it proving that it works in theory, and level 4 is when a technology has a functioning lab model. This project is the bridge between 3 and 4, since the goal of this project is to build a functioning lab model of the GREC. [1]

1.1.2 Technology behind GREC

The GREC is a heat engine which works with inspiration of the Carnot cycle, where a fluid is heated so that it expands. The principle of the Carnot cycle is that it is at maximum efficiency, and this because only consists of reversible cycles. A reversible cycle is impossible to achieve in practice, meaning the Carnot cycle is a fully theoretical cycle. A reversible process means that no energy is lost due to for example friction during the cycle and that the process returns to the initial state with the initial energy level. The desired energy output and input are the only energy transfers that take place during the cycle. See figure 1 of Carnot cycle below. [2]

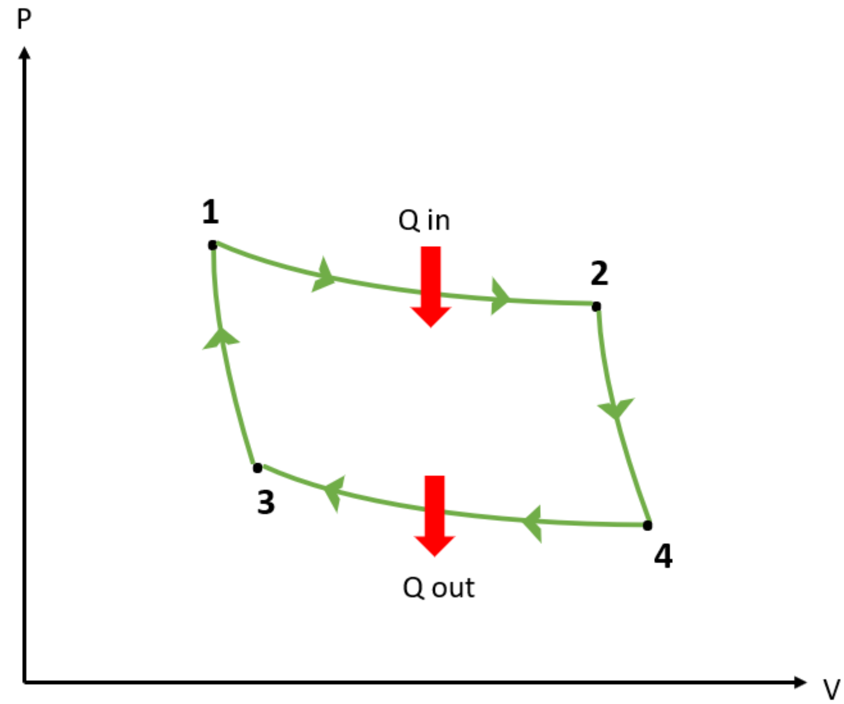


Figure 1: Pressure-Volume diagram illustrating the Carnot cycle. Red arrow Q in illustrates heat source that adds energy, whereas Q out illustrates the cold source where energy is reduced.

When the GREC motor was designed and developed, the theory of the Carnot cycle was used as base. The GREC is designed so that there is one heat source and one cold source, just as with the Carnot cycle. Between the warm and cold part of the GREC, the rotating part of the motor itself is placed. The motor works by rotating a fluid that expands because of the heat source and thereafter rotates to the cold side which then produces a pressure difference (see Figure 2). Work can be extracted from this expansion and thus energy can be produced. The fluid is moved by a revolving shutter (RS), which is essentially a disc with a section cut out. The volume of this section is what makes up the Work Generating Volume (WGV). The RS rotates by having an electric motor connected to the axle which is placed in the centre. The fluid is heated and cooled by Conducting Fins which are put on opposite sides of the GREC in a configuration that allows heat only to transfer between these by convection to the fluid. There are insulating fins between the conductive fins to inhibit contact heat transfer.

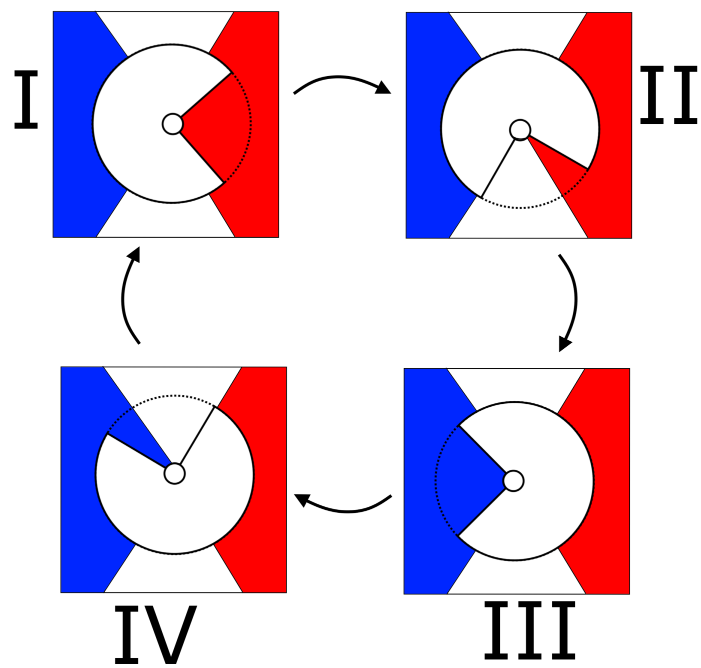


Figure 2: Illustration of a cycle of the GREC. Red part illustrates the heat source, and the blue part the cold source.

In figure 2 the cycle of the GREC is illustrated. Step I is where the WGV is heated. Moving to Step II where the RS rotates the WGV from the warm part to the neutral part, where the air expands to build pressure. Step III is where the WGV has been rotated to the cold part and this is where the pressure difference is produced when the WGV is cooled down. Lastly step IV is when the WGV is rotated back to step I and here also passing by a neutral part.

Since the RS is actuated using a electric motor the goal of GREC is to extract more work from the pressure difference inside the engine than is used to run the electric motor. The energy for heating the fluid is supposed to come from waste heat from different industries or really any process which produces heat as a byproduct.[1]

1.1.3 Previous Work

The previous work for the GREC engine has been studied in different projects. The first project was conducted in the spring of 2022 by five students from the Department of Management and engineering. This project set the foundation for the rest of the research for the GREC engine therefore this will be one of the main basis for the study. The published result is called: **Theoretical**

Proof Of Concept For The Green Revolution Energy Converter: Development of a mathematical model, material analysis and physical model improvements. The main objectives from the study consisted of;

- Creating a proof of concept for the GREC engine
- Studying material selection for crucial parts of the engine
- Analyzing construction improvements from the initial design

Regarding the proof of concept the main results found were that a high temperature difference between the heat sources is desired. This in order to achieve the highest possible power output and efficiency. The size of the engine was also found to be of interest, larger scales showed to be more effective and efficient.

The material selection studies were mainly performed for three engine parts, the conducting fins, the isolation as well as the revolving shutter. Copper was found to be the best material for the conducting fins when regarding effectiveness, however aluminium was also found to be a candidate when considering price. Bakelite was the clear choice for isolation material when considering performance and price. This is because bakelite distributes the heat well in the isolating fins and is cheap. ABS 10% carbon fiber was found to be the best material for the revolving shutter since it provides low heat transfer within the material and has a high yield limit. Polystyrene is considered to be viable at low rpm and temperature since higher values for these parameters might cause the material to break. The material is also five times less expensive than the ABS 10% carbon fiber. [3]

Furthermore another project was conducted in the project course TMPE09 in the fall of 2022. The report is called **Investigation of the internal heat transfer of GREC** and studied how the design of the engine effects the pressure difference and work output. The project also investigated how turbulence in the WGV effected the pressure and work. The results indicated that a slow rotation speed of the RS and a thin WGV leads to a greater pressure difference within the WGV. When the RS is rotating slowly the heat rate is increasing which results in a higher generated work output. To reach a high generated output it is concluded that a higher temperature difference between the hot and cold side is needed. Turbulence in the WGV also increases both the generated work and pressure difference. However the scope of the project was not to decide how the turbulence is created but only how it affects the heat transfer.

The same report also looked in to different designs of the RS. The project investigated the how design effected heattransfer. The design tested were 1/8 instead of 1/4 of the RS cut out, the results of this was that heat transfer increased with this design. A main conclusion from this project is that if a high temperature difference is possible a large rotating radius is desired. [4]

1.1.4 Organisation

The organisation of this GREC project is divided into three groups of three students, and together the groups cover the mechatronics, the thermodynamics and the construction and designing of the motor itself. The groups will work separately with their respective area of the GREC, but will consistently discuss and keep a dialog going so that there will be no misunderstanding or double work.

1.1.5 Existing electric system

The first lab model that was created by the inventor of the GREC had built up the electric system by two Arduino Uno and one Raspberry Pi. This lab model was already at place on LiU for the start of this project, which made research about the existing system easier. The Arduino units were used in order to control the motor and sensors, while the Raspberry Pi was used mainly as a computer to run and program the Arduino's. The Raspberry also acts as a memory for the data collected by the sensors. The current system is missing a proper wiring diagram. The motor used to move the RS is a NEMA17 stepper-motor from STEPPERONLINE. The sensor used to measure the pressure in the current system is a single BMP280 Barometric Temperature and pressure sensor positioned close to the center of the GREC (just above the motor in the picture). To measure the position of the RS a magnet is fitted to the edge of the RS which is detected by Hall-effect sensors positioned around the circular travel path of the magnet, so when a hall sensor is activated the system knows where the RS is. In figure 3 is a picture displaying the previous electric system.

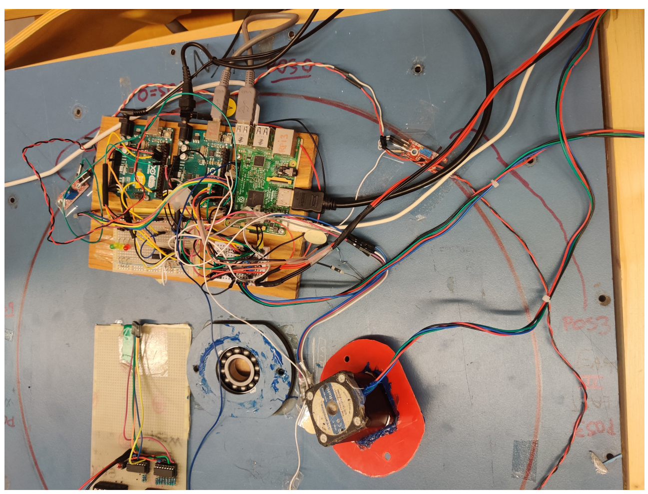


Figure 3: A picture of the current electric system for the GREC. A stepper-motor glued to a red plate is visible in the picture as well as the Arduinos and the Raspberry Pi

1.2 Literature

During the work on the mechatronics of GREC different sources and methods will be used. Before any actual work on the mechatronics of GREC begins research on the background, company (nilsinside AB), technology behind GREC and previous work is done to gather information and get a bigger picture of the work ahead. The information in these sections is gathered mainly from the website of the company of nilsinside AB, and also from previous reports on the GREC.

Going forward, a big part of the theory in the rest of the work will also be based on information gathered on the website of nilsinside AB and previous reports from students on LiU. Gathering information on different sensors and electrical motors will however be done by looking at data sheets found on the suppliers websites, as well as sites or reports containing relevant information.

Throughout the whole work the reasoning around GREC and its mechatronics are mainly based on general theory that can be found in textbooks regarding mechanics, thermodynamics, material theory and mechatronics.

1.3 Purpose of the project

The purpose of the project regarding the mechatronics of GREC is to get the revolving shutter rotating with the use of an electric motor, and also to retrieve measurable data from the different sensors.

1.3.1 Project goals

The goal of this project is to produce a functioning prototype of the GREC as a physical proof of concept. This is to be determined mainly by achieving a measurable pressure difference from the prototype. This project is executed by three different groups which all have more specific objectives in their respective fields.

The mechatronic part of the GREC project will have the following specific goals:

- Choose an electric motor which is strong enough to actuate the revolving shutter
- Choose suitable sensors to measure pressure in different regions of the GREC, as well as the position and speed of the revolving shutter.
- Write code to both control the electric motor and access the readings from the sensors and design a wiring diagram.

1.4 Research questions

RQ1. What factors should be considered when selecting an electric motor and driver for the GREC?
There are a few various types of electric motors that works in different ways and could therefore affect the powering the GREC differently. These motors require different drivers which can alter the electric motors performance.

RQ2. How does the choice of microprocessor influence the capability of the GREC motor?
Different computers have different capabilities when in comes to programming, compatibility and multi threading.

RQ3. In what way does the choice of sensors alter the quality of the measurements for the GREC?
Different sensor have different resolution and measuring frequency. Depending on what sensors are chosen the result may have different outcomes.

1.5 Limitations

Factors that can limit the outcome of the project:

- The RS is not able to spin due to friction, stopping the group from getting good and clear results.
- Slow deliveries of components can result in a delay of the entire project.
- The heating and cooling of the GREC is insufficient, resulting in no pressure difference being built up.

1.6 Delimitations

In the original concept the engine will have a modular design and the modules with heating/cooling fins and shutters will be stackable. In this report the construction and calculations will focus on only one engine layer. This GREC model will be designed so that the results obtained from calculations on one module will easily be translated to a bigger engine consisting of more stacked units. Because of this the motor we choose does not have to produce as much torque since it only has to move a single RS.

The GREC motor for this project will be at a stage where it does not have to produce more energy than it consumes from the electric motor since this is only a prototype and a scalable version of the finished GREC. The purpose of the GREC is to act proof of concept and to show that it could potentially produce a pressure differential substantial enough to harness for energy production.

We do not take any mechanical friction in to consideration. This is because the goal of the "Construction Group" is to make the GREC friction less (besides a small negligible friction in the ball bearing).

The prototype will be assumed to be air tight (included around the sensors). This results in that all the difference in pressure will be measured by the pressure sensors

We will not be looking in to using other types of micro controller than Arduino Micro controller. The group already have knowledge of using Arduino and also have Arduinos available, and will therefor not have to wait for deliveries before testing code.

1.7 Budget

The budget for the project will be around 12 000 sek for the whole project of GREC. The money will be divided between the different groups of the project depending which group is in the most need of the money for purchases. For the mechatronics of GREC there will be purchases of sensors, control boards, motor etc. which will require a part of the budget. If needed, the project will receive additional funding.

1.8 Ethical reflection

Building the GREC motor is a contribution to a more climate efficient world. The GREC is planned to work using waste heat from primarily industrial processes to power the motor instead of for example fossil fuels like many other motors. There is currently a big aspiration in society to develop alternative energy sources that does not contribute to the global warming. The completion of this project will in first hand favor the inventor of the GREC, who owns the patent of the motor and also runs the company nilsinside AB. It is impossible to predict the long term future of the GREC after this project, but with a hopefully functioning prototype there is definitely opportunity for further development of the motor and its area of use. Possible disadvantages for other stakeholders in the motor industry because of the construction of GREC is the competition against other motor constructors. Short term disadvantages of the GREC are however considered to be minimal, where the previously mentioned competition for the motor constructors may be a long term effect if ever arisen.

Invalid or incorrect results of the construction of the GREC may cause inadequate information for any future work for to build on. Wrongful construction can also cause a breakdown which could possibly be harmful for a user if broken while running the motor. Incorrect heating of the GREC could also possibly be harmful if making contact with the warm parts. Correct use of everything should not be any danger or risk of harm for any person. The environment could however be damaged if parts of the motor are discarded without the correct recycling. The results of the construction the GREC model are with big probability not dangerous to be spread out to the general public, since nothing about the invention is considered dangerous or secret.

If the performance of this project is not satisfactory or incomplete the consequences could be a lot like the disadvantages mentioned above which are a possible harm if the motor breaks or is used incorrect. This in turn could also lead to false or misleading information for further work to be based upon if not clearly stated in the conclusion. The spread of false results from the project of designing the GREC is estimated to not be any big risk for society or other interested party, since the concept of the GREC motor is based upon already existing and commonly known theory about thermodynamics. It is therefore judged not to be necessary for any critical risk analysis, but just a general estimation about the risks of the project.

2 Theory

In this section, theory regarding different fields will be presented. This include: Electrical motors, Sensors and Control systems.

2.1 Electrical motors

There are several types of electric motors, some of the most common types will be presented below.

2.1.1 DC

A DC (Direct current) motor is an electrical motor that works by running a current through coils which induces a magnetic field around the coil. This field pushes on a stator, which is a permanent magnet. Usually DC are brushed, which means that the way the electromagnets are energized is by a stationary physical connection (literal copper wire brush) where the direction of the current changes at certain angles so that the magnetic force is always in the correct direction to make the motor spin. Typically the stators are around the perimeter and the electromagnets are the ones that spin in the middle. The speed and torque of a DC motor is controlled by the volts and amperes supplied, thus they are easy to control with only a battery and variable resistance, or just controlling the supplied voltage and current. [5]

2.1.2 BLDC

A BLDC (Brush Less DC) works almost like a regular DC motor, but with the difference that the permament magnets are usually in the middle part that spins and the stators are electromagnets are around the perimeter which pushes the permanent magnets in the center. The advantages that a BLDC motor has over a regular DC motor is that the internal friction is reduced since the moving parts doesn't have a brush connected to it. The brush not only adds internal friction, but since the material of the brush will inevitably break down due to the friction there will be a buildup of dust inside the motor so maintenance will be required, which is a problem that a BLDC motor will not have. However BLDC are usually more expensive than regular DC motors as well as most stepper motors, but they are usually more efficient and has a higher power-to-weight ratio than most other electrical engines. [5]

2.1.3 Stepper

A stepper motor is similar to a BLDC motor but usually with a lot more electromagnets so that it is possible to take smaller, more controlled steps. The advantage that stepper motors hold over regular DC motors is that they can very accurately control their position. Since stepper motors takes small "steps" with a set angle. To take a single step the micro controller sends a pulse to the motor driver which energises the coils inside the motor in sequence. The maximum speed that a stepper motor can achieve is limited by the frequency that the micro controller can send pulses as well the supplied voltage, since if the voltage is too low the coils might not charge up enough to actuate the rotor which results in the motor skipping a step or stalling. Stepper motors use a driver that regulate the input current to keep the motor from overheating as well as controlling the order and speed the coils are energized so the motor can spin. The downside of stepper motors are that they are better suited for low-speed high-accuracy applications, and not were high speed and torque is required. Most stepper-motors are limited to a speed of around 3000 RPM and with a steep drop in torque as the speed is increased. As long as the motor is unloaded the speed can also be controlled very accurately since it is directly controlled by a computer. When speed is not accurate is if the motor is experiencing a load which might make it skip steps, this basically gives an inherent maximum speed since the motor does not have enough torque to overcome the inertia and accelerate whatever the motor is moving beyond a certain speed.[6] [7]

Stepper motor drivers are also capable to energize the coils in such a way that the motor can take half steps or even smaller fractions of a step, a process called micro-stepping, depending on the driver. This is used when one needs a higher number of steps and thus a higher accuracy. Micro stepping does however come with the downside of needing to send more pulses to the motor for a full rotation, thus limiting the maximum speed depending on which frequency the micro controller can send pulses. Another downside is that the holding torque of the motor reduced drastically with the amount of micro steps per full step, resulting in a more accurate but weaker motor.[8]

2.2 Sensors

In this section, theory for different types of sensors will be presented.

2.2.1 Pressure sensors

There are three types of measurements of pressure, Absolute pressure, Differential pressure and Gauge pressure. There are different types of pressure sensors that work by more or less the same principle, to measure the deformation of some kind of element, which are more or less suitable for different situations.

Aneroid Barometer Pressure sensor is a sensor that is purely mechanical and it works by detecting the deformation of a hollow capsule and then displaying this deformation as the pressure change using a mechanical dial. Due to how the Aneroid Barometer Pressure sensor works, the sensor is slow and does not react rapidly to pressure change, and depending for the material used for the capsule element, the sensor can measure in different pressure ranges. [9]

Manometer Pressure sensor works using a glass tube filled with a liquid. The most common Manometers are using an U-shaped tube, and when the tube is exposed to pressure the liquid is displaced, this causes a drop in liquid level at one side and a rise at the other end. This difference is then measured and displayed as the pressure. [9]

The **Bourdon Tube Pressure sensors** works more or less by the same principal as the Manometer, however it uses a C-shaped element instead of an U-shaped. It does not displace a liquid but instead the deformation of the element causes a coil to compress or extend, and this does in extension translate to a pressure that can be presented using a dial. [9]

Vacuum Pressure sensor is a sensor which main purpose is to measure pressures below atmospheric pressure. It works by measuring the resistance of a heated element. As the surrounding pressure decreases, the thermal conductivity decreases and therefore also the temperature and in extension the resistance of the element. This can easily be measured. [9]

Sealed Pressure sensors is a sealed sensor that has a reference pressure inside of it. When the ambient pressure increases or decreases, a deformation takes place, this is compared to the reference pressure and can be displayed as electrical signals.[9]

Strain Gauge Pressure sensor, as the name suggest the sensor measure the strain on a material using a strain gauge, which can be translated into pressure. [9]

A **piezoresistive pressure** sensor, usually made with silicon for consumer grade, consists of two pieces of silicon, one thin diaphragm layer (membrane) and a support rim. Piezoresistors are implanted into the silicone membrane near the edges. When the sensor is exposed to a negative or positive pressure, the diaphragm bends outwards or inwards causing the piezoresistors to compress or extends which alters the resisting characteristics of them. The change in resistance can easily be meassured, and since this is highly related to the compression/extension of the piezoresistors, and in extension the membrane, the pressure can be calculated. The piezoresistice pressure sensors can measure small pressure differeces and can theoretically measure changes in pressure in one millisecond. [10]

2.2.2 Hall effect sensors

Hall effect sensor is a sensor that produces an electrical voltage from magnetic fields. This characteristic makes the sensor suitable for sensing the position of different things that are magnetic.

The sensor basically works using a semiconductor, and when this piece of semiconductor is placed in a magnetic field the electrons within the conductor moves towards one side (depending on how it is oriented in the magnetic flux). This increases the electric potential, and this generates a voltage, indicating that the semiconductor is exposed to a magnetic field. Essentially hall sensors can function as a switch which turns on when it is inside a magnetic field, but they can also measure how strong the magnetic field is.[11]

2.2.3 Temperature sensors

The way that temperature sensors work is that they generate either a voltage or resistance when the temperature changes. They consists of two metal parts between which the voltage or resistance occurs. A temperature sensor can either be in contact to the material or not, and these two types of temperature sensors therefore work and is built differently. The sensors that are in contact with the material is used for example when measuring temperature in a solid, liquid or gas material, while the sensors not in contact are used for example by measuring radiation from a heat source. For this project the type that would be the best suitable is the temperature sensor that needs to be in contact with the "object" desired to measure.

When choosing between different temperature sensors, it is important to know which requirements that the sensor have to meet, for example in which temperature range it is going to work in, or which response time is needed. There are three types of contact temperature sensors mainly used in different industries, and those are Thermocouples, Resistance temperature detectors (RTD) and Thermistors. These vary from each other in terms of the temperatures at which they start working and the temperatures they work up to. Additionally, they exhibit distinct response times, varying levels of accuracy, and different costs. [12]

2.3 Control system

Control systems is a way to make things act a certain desired way. It can be technical, biological, economical devices such as cars, airplanes, a country's economy, a lake or different industrial machines. These "systems" have different variables that affect the system, also called signals. The aim is to control these signals in the correct way so that the system behaves as desired.

The approach for this is that a variety of signals need to be measured and taken into consideration when controlling the system. One of the different signals are outsignal, which is the actual value of what is happening in the system at the moment, for example which velocity a car is driving in. The signal that controls the system is the input signal, such as how much gas is given to a car. These two signals are put into relation to a reference signal, which is the desired value of the system, for example the desired velocity of a car in cruise control. The difference between the outsignal and the reference signal is called the regulation error. Another signal that affects the whole system is a signal that is unable to control manually, is an interference signal, which could be such as air resistance, magnetic waves, electrical interference such as unknown frequencies etc.[13]

There are two different types of ways to control a system, one is through open control and the other is with a feedback signal. The open system is only regulated by an input signal, and no regard is taken to the current state of the system. A feedback control system however, is controlled through a feedback loop from the outsignal. The outsignal is measured and the input signal then is sent in as feedback based on how far from the reference signal the outsignal is.

Together with the outsignal this feedback signal is calculated into a control signal, and this process is called PID-control. A PID-controller stands for a proportional-integral-derivative controller, which consists of the three parameters and is abbreviated to PID. To start with, the proportional part acts directly in regards to the regulation error. The bigger P-part, the greater the chance for instability. The integral part strives to drive the regulation error towards zero. In theory the regulation error can be zero, but in practice there are always interference that makes achieving zero error almost impossible. Lastly the derivative part acts as a moderating factor, and operates through the changing of the outsignal. The quicker the outsignal changes, the smaller regulation from the derivative part is necessary.[14]

2.4 Arduino

Arduino Mega is a microprocessor board that is based on the ATmega2560 microprocessor. The board hosts 54 digital input/output pins and 16 analog input pins. The standardised pins on a board allows users to connect a lot of different third part components, which communicates with the Arduino board either through the digital pins, or through the I2C protocol. The Arduino boards use a default 5 V as operating voltage and a 16 MHz crystall oscillator. Arduino also offers a smaller, but less powerful microprocessor called UNO. Just as the Mega, it has digital input and output pins, analog pins as well as pins for I2C communication. In figure 4 and 5 a picture of an Arduino Mega respectively an Arduino Uno is showed.

Arduino IDE is based on Java, and is developed with the user in focus. This makes the interface user friendly and more accessible for people not used to programming and software development. The IDE also has a single button to compile the code and then upload it to a connected Arduino Board.

The Arduino works by sending signals via the pins, either analog or digital. The analog pins can take any number as value, while the digital pins just can take the value 0 and 1, or as it often is referred to, LOW and HIGH. [15]

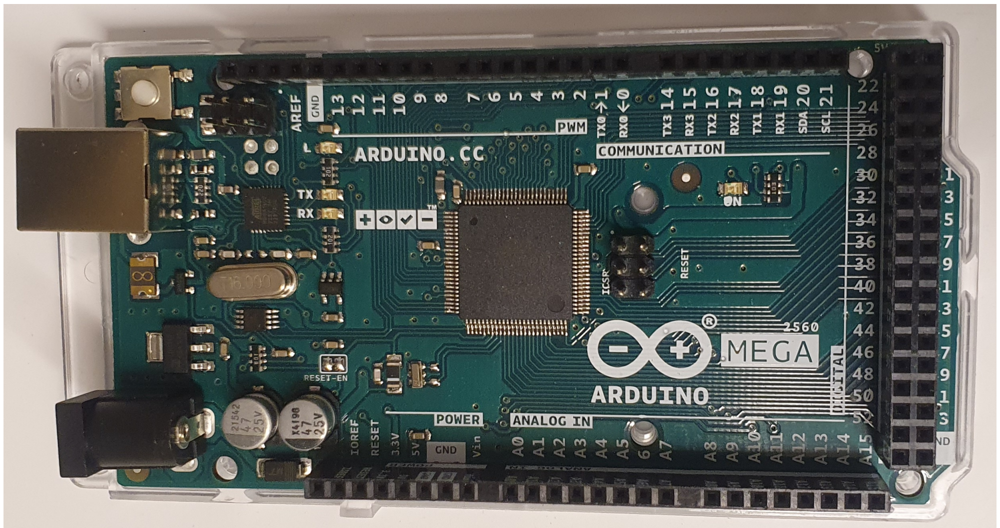


Figure 4: A picture taken with cellphone camera showing the Arduino Mega 2560 used for the project.

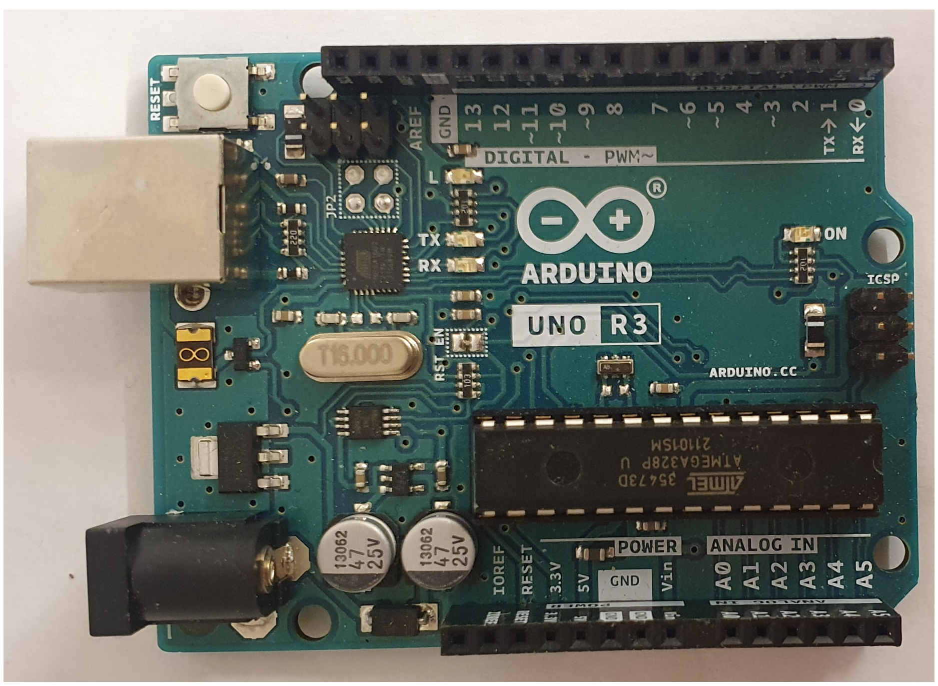


Figure 5: A picture taken with cellphone camera showing the Arduino Uno used for the project.

2.4.1 I2C protocol

The Arduino can run I2C protocol, which is a way to simplify and structure communication between different devices. I2C is a powerful protocol that allows the user to communicate between a master unit and up to 128 slave units, using only two wires, Serial Clock (SCL) and Serial Data (SDA). The SCL works as a synchronisation between the master and the slaves while the SDA wire carries the data transfer. The commutation is sent in sets of 8 bits, after every such set, a bit called Acknowledge is sent.

To start the commucation, a start condition is required. This occurs when the SDA wire drops to "LOW" while the SCL line is still "HIGH". Once the communication is started, information about the device address is sent in 7 bits. This ends with a bit called Read or Write, which indicates if the master should write to the slave or read from it. Between each set, there is a bit called ACK/NACK sent, this indicates if the communication is working as expected, if the slave understands the communication or if any unit is busy and therefore can not communicate. This is followed by the internal register adressing, which contains information about what type of infomation that is sent. As an example, if a sensor can read both pressure and temperature, the internal register addressing help to indicate if the data recived in the following set of bits is pressure or temeperature. The communication ends when the SDA line goes from low to high while the SCL is high.[16]

3 Calculations

In this section, the calculations needed for the project will be presented. The measurements of the RS will be taken from Table 1 below.

Table 1: Table showing the different variables of the RS and a description of what they mean, as well as the dimension.

RS dimensions		
Variable	Description	Dimension
r	Radius of the RS	0.21 [m]
b	The width of the flange	0.17 [m]
t	The thickness of the RS	0.08 [m]
A	The area of the flange	0.0136 [m^2]
L	The length of circumference	0.99 [m]

3.1 Friction & Torque

One assumption that was made in order to calculate this was that the GREC will be frictionless from mechanical friction. In other words, the RS will not be scraping against the inside of the GREC, and that friction in the bearing can be neglected. The remaining force acting upon the RS is the friction from air flowing along the surface and the air resistance from the surface area on the flange of the inside of the WGV.

Flow along flat surface The total force is given by:

$$F_{D1} = C_D * r * L * \frac{\rho}{2} * U_\infty \tag{1}$$

For this we need the drag coefficient which is given by:

$$C_D = \frac{0,074}{Re^{\frac{1}{5}}} \tag{2}$$

To calculate this we also need to calculate the Reynolds number:

$$Re = \frac{\rho * U_\infty * L}{\mu}(3) \tag{3}$$

with (1), (2) and (3), we get a final equation to calculate the force:

$$F_{D1} = \frac{0,074}{2} * \mu^{\frac{1}{5}} * (\rho * U_\infty * L)^{\frac{4}{5}} \tag{4}$$

With values, this gives a total force from the flow along the surface

$$F_{D1} = 0,007N \tag{5}$$

Air resistance from flange area

Furthermore, the flange of the RS will hit the air and therefore slow the RS down and a force will be induced. This force can be roughly calculated as following:

$$F_{D2} = \frac{V^2}{2} * C_D * \rho * A \tag{6}$$

Where rho is the density of the air, V is the maximal speed along the flange (the most outer part), the drag coefficient for an approximated cuboid and A is the area exposed to air. All mesurements have been taken from the construction group.

$$F_{D2} = 0,98N \tag{7}$$

Total force & Torque

The total force that we need to overcome with the motor is then:

$$F = F_{D1} + F_{D2} \tag{8}$$

$$F = 0,99N \tag{9}$$

In extension, this means that the motor need to be strong enough to overcome these forces at maximum speed.

$$M = F * R = 0,23Nm \tag{10}$$

Due to many estiamtions in the calculation, the group decides to use a safty factor of 2, resulting in the following:

$$M_S = M * 2 = 0,46Nm \tag{11}$$

3.2 Frequency

Calculations are made to determain what frequency sensors have to be able to measure at in order to get good measurements at 500 rpm.

$$f = \frac{500}{60} = 8,33Hz \tag{12}$$

4 Method

In this section the theoretical and planned method will be presented.

4.1 Choosing sensors

The sensors needed for the GREC were chosen from specific requirements. The requirements for each sensor was decided given the circumstances and what is to be measured. Determining these values was done by concluding information from the calculations done in the previous chapter and also by using information from . By compiling a list for each of the sensors and from this list a suitable sensor was decided.

The parameters for the different sensors are:

Pressure Sensors

- Be able to handle a pressure difference of 5 kPa compared to atmospheric pressure, with a safety factor of 10.
- Have a update frequency of 10 Hz or more to be able to read the pressure change at least once per revolution (see equation (12)).
- Easy to incorporate in the GREC without causing air-leaks.

Temperature Sensors

- Measure temperature in a span from -10°C to 300°C, this is more than we expect, but we want a safety span for future research projects.
- The sensor should be able to measure a frequency of at least 10 Hz to record the change in pressure (see equation 12).

Hall Sensors

- Be able to turn on and off fast enough to register the magnet connected to the RS rotating at 500 RPM (from previous work).

For every required application (temperature, pressure, position) there was different ways to measure the values, using different types of sensors. First of all, the type of sensor needed to that specific sitiuation was decided.

When the type of sensor is decided, the exact sensor is decided by comparing data sheets for different models of sensors. When deciding on the final one, price and what company that had the product in stock, as well as what companies Linköping University has an agreement with, was taken in to consideration. Since the project worked on a relatively tight budget, the decision were guided by which sensor fits in to the economical aspects while still being acceptable to our requirements, rather then the sensor that would be best for our application.

4.2 Designing wiring diagram

To make it easier for future work to pick up how the motor and sensors are connected we will make a comprehensive and easy to understand wiring diagram that shows how everything is connected. This will be an important part since the physical wiring can get tangled and if there is no reference to a working wiring it will be much more difficult to rewire something in the future.

When designing the wiring diagram, one of the first steps is to gather the electrical symbol of every component that will be used. The symbols are then placed in an approximate order and structure of the electrical connection made in real life, and a wiring diagram will be drawn from there. Preferably the wiring diagram will be designed so that, if possible, not too many lines cross each other and contributes to unnecessary confusion. The schematics of the wiring diagram will be made in a program called *LTspice xvii*, where new symbols can be designed which makes it possible to simplify and illustrate the wiring being made.

The physical wiring will be made up of one Arduino which will hold the code that will run the motor and one that will take readings from the sensors. There will also be a few breadboards to connect the different sensors, a multiplexer, a stepper motor driver and the sensors themselves. Lastly the stepper motor itself, a power supply and a start button will be included.

4.3 Choosing electric motor

As with deciding which sensors to use, the electric motor is also decided by which motor type is most suited for this project. After the type of motor is chosen, there are other considerations to take into account. These include: price, availability online from the suppliers approved by Linköping University, and what torque and speed characteristics the motor has. From the calculations made in the previous chapter, a list of requirements for the motor was compiled.

Electric motor

- Be able to spin the motor at 500 RPM atleast, to be on the safe side and futureproof the motor, a speed of 1000 RPM was required.
- Be able to overcome any unexpected mechanical friction, thereby we want a minimum torque of 0.5 Nm at 500 RPM (see equation (11)).
- Control the rotational speed with ease.

The torque of the motor is also what determines how fast the RS can accelerate, but with a low torque motor this just means that the RS will need to accelerate slower than a stronger motor. The GREC should be constructed in such a way that there is no friction acting on the RS other than that from the bearings on the axle and the air resistance when the RS is moving. These forces are small and would not require a very large electric motor to overcome. But since this is a prototype GREC with the main purpose of testing how much of a pressure difference one can get inside the engine, we decided that in case the RS bends or wobbles and comes into contact with the internal walls of the GREC the electric motor should have a large enough torque to overcome a small amount of unexpected friction.

In order to control the electric motor, a control board is required. This component more or less just had one hard requirement, that is to be compatible with the motor that was decided on. Since the group works on a tight budget, the group also needed to minimize the price as much as possible on components that does not have too specific requirements, without compromising the performance.

4.4 Code and Collection of data

In order to make the electronics of the GREC to work some code will need to be written. Since an Arduino is used, the Arduino IDE can be used, which as previously mentioned in the theory is a program based on Java with a user friendly interface. To make the GREC work as expected the code first of all needed to make a motor rotate, this was done using a simple motor control where the desired value for the speed is set, and then by using a feedback loop with the Hall sensors as speed detection, controlled to make sure this speed is maintained without any static errors or variations. To make this feedback plausible, the current speed of the RS need to be recorded, this is done using Hall sensors and then calculate the current RPM.

When the speed feedback was working the group set out to collect data from the sensors, this was done by using code to record the current pressure of the different sensors, then recording this using a third part program, since the Arduino does not have any integrated memory. As previously mentioned, the location of the RS can be detected using the Hall sensors, the code was written in such a way the pressure different that i measured can be referenced to what the orientation of the RS is at the time of measurements.

4.5 Design of control system

The control system will be a simple but effective feedback loop to control the electric motor. Depending on which electric motor is chosen the system will look different. The main purpose of the control system is simply to measure the speed of the RS and compare it to the motors set speed. This control system will make sure that the speed of the RS is regulated so that sensor readings can be attached to a specific RPM.

4.6 Testing and validation of GREC

A testing period will be carried out where data will be collected and everything will be tested and adjusted to fit eventual problems. Some of the mechatronic part of the testing can be done before the GREC as a whole is assembled. Since the main part about testing the mechatronics is to make sure that the electric motor spins and that the sensors readings can be viewed. With the GREC assembled the electric motor and sensors should work the same as when they are not in a "live" setting, only difference being that when connected to the finished GREC the motor will actually perform its function and move the RS while the sensors will measure the pressure difference in the WGV.

The preliminary plan of testing the sensors and motor control before the GREC is assembled will be to draw the RS full scale and lay out all the sensors at the correct place and confirm that the wiring and code works as it should.

4.7 Order of purchase

In the chapter Delimitations it was stated that Arduinos will be used for this project. From this, the first component to be purchased and chosen is the electric motor, since that is vital for the rotation of the GREC. The motor is chosen from the requirements of the RPM as well as the assumed resistance inside the GREC.

The remaining components are to be chosen based on these two first components. The electric motor driver is for example based on the electric motor. The sensors are chosen to be controlled easily by the Arduino.

5 Results

In this section, the result in for the project will be presented. That includes what hardware that was used, what code that was needed, the control system for the GREC and also the results from testing the engine.

5.1 Sensors

Pressure Sensors
The pressure sensor picked is the MPRLS0025PA00001A fitted on a Qwiic Micropressure Sensor board from Sparkfun. Figure 6 below shows the sensor from two different angles.

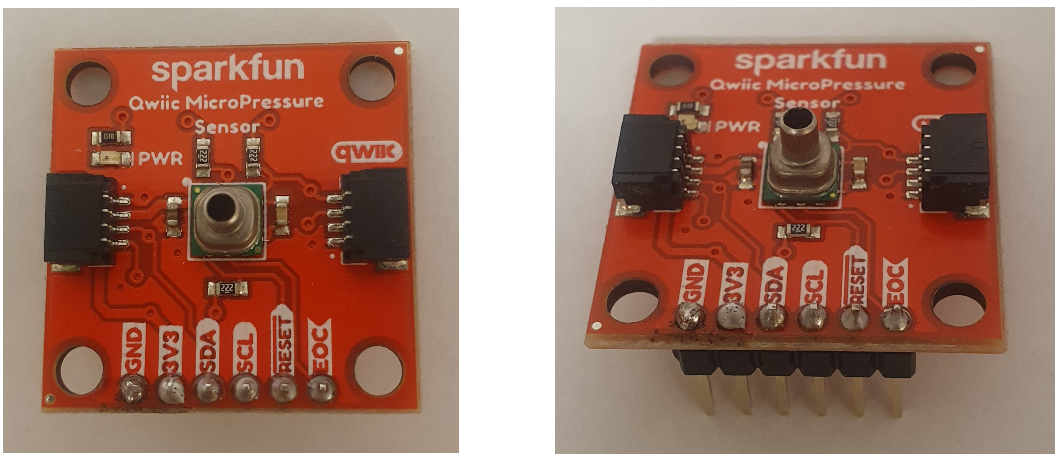


Figure 6: The micropressure sparkfun sensor.

Table 2: Table displaying some interesting data regarding the chosen pressure sensor.

Range	6 - 250 [kPa]
Frequency	160 [Hz]
Communication	24-bit I^2C

Table 2 shows relevant data for the pressure sensor chosen. This sensor can measure pressures between 6 kPa and 250 kPa. This covers the complete spectrum that is expected from calculations and goes beyond that. The sensor can also measure up to a speed of 160 Hz, which is high enough in our application. The long port configuration of the sensor allows the sensor to be fitted with an O-ring and combined with a manifold designed into the shell of the GREC, the sensor should hold air tight. [17]

I2C Multiplexer

Another component chosen is the I2C Multiplexer, this to split the signals and to be able to read all the pressure sensors at the same time. Figure 7 show the Multiplexer chosen.[18]

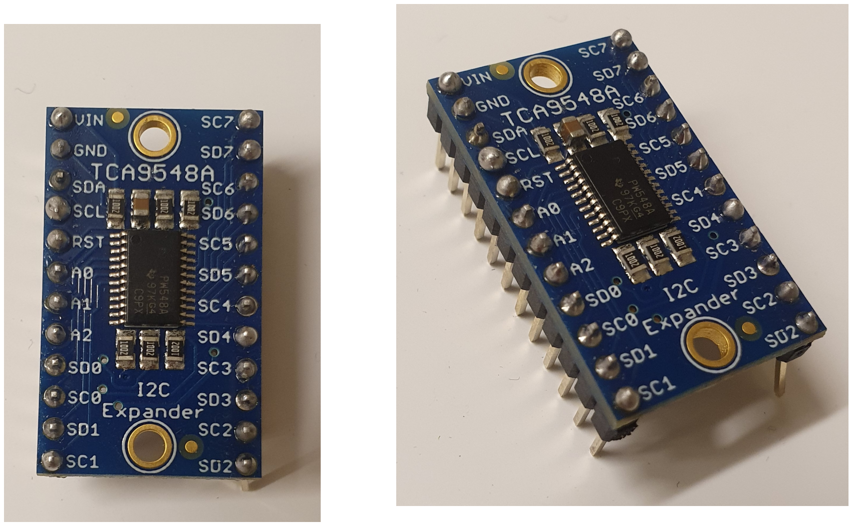


Figure 7: The I2C Multiplexer component.

Hall sensors

The Hall sensor that was picked for our application is the SS49E, mounted on a board that makes it easier to set up, and connect to.

Table 3: Table displaying some interesting data regarding the chosen hall sensor.

Response Time	3 [μs]
Temperature error	0.1 [%/°C]

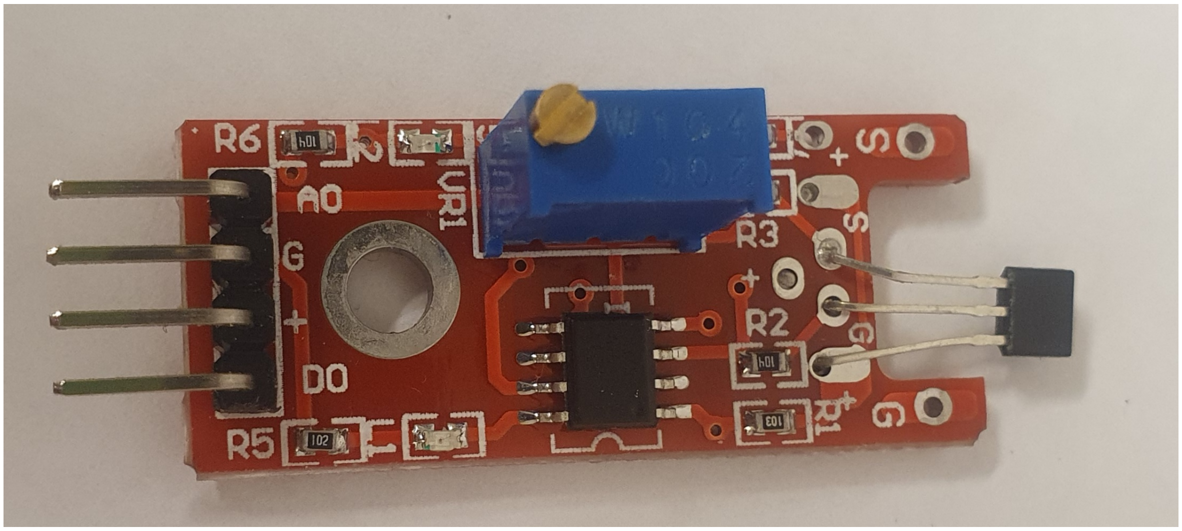


Figure 8: Hall effect sensor

Table 3 displays relevant data for the chosen sensor. This is a sensor that meets the requirement, and besides that the sensor also had a small error due to temperature, which is something that can come to be interesting as the temperature in the GREC rises. [19]

Temperature sensor

No sensor fitted the requirements, therefore, no sensor was decided on for this application. All of the sensors that where within our budget constraints had a too low of an update frequency to be useful for the GREC.

5.2 Electrical motor

From the requirements set for the motor we decided on using a stepper motor to actuate the RS. The motor chosen is the SM2564C60B41 NEMA 23 1.8°motor from Sanyo Denki which will run on a voltage of 24 VDC as shown in Figure 9 below. The motor can produce ca 0.7 Nm of torque at 1000 RPM, and ca 1.5 Nm of torque at 500 rpm. It also has a theoretical maximum speed of 3000 RPM with the right driver. The motor has a maximum self start frequency of ca 1500 pulses per second, which means that unloaded the motor can go from 0 RPM to about 450 RPM instantaneously. To connect the motor to the driver the Bipolar motor cable 4837961-1 was used. Figure 9 shows the stepper motor chosen. [20]

Figure 9: The electric stepper motor.

For this motor a DRV8825 steppermotor-driver was used (see Figure 10). It has a voltage operating range of 8.2-45 VDC which fits the chosen motor. It does however only supply a maximum current of 2.5 A at 24 VDC. This driver is however not a perfect match for the motor but was chosen because any drivers that are perfectly compatible were far too expensive for this project. In figure 10 the stepper motor driver is shown from two different angles. [21]

Figure 10: The stepper motor driver DRV8255.

5.3 Microcontroller

The Microcontrollers chosen for the system was one Arduino Mega 2560 and one Arduino Uno. The Arduino Mega has 54 digital pins and 16 analog pins. The Arduino Uno has 16 digital pins and only 6 analog pins.

5.4 Code

The code was written in two parts, one to control the stepper-motor, which accelerates the motor and then runs it at the desired speed. The other part of the code reads the sensors and prints it. The motor-control code runs on the Arduino Uno and the sensor code runs on the Arduino Mega. See Appendix A for the complete code and the Figure 11 of a schematic overview for how the code is structured.

The sensors were able to be read properly and the pressure-data, RPM and position were able to be directly transcribed into a Microsoft Excel file for easy analysis. Normally the values measured by the Arduino can only be read within its own app in the serial monitor. The way this transcription to Excel was done was through an Add-on in Excel simply called "Data Streamer" which works by intercepting the signals that would go to the serial monitor and instead sends them to Excel.[22]

5.5 Wiring diagram

The program *LTspice xvii* is used to design the symbols for the components used. In Table 4 and Table 5 below, the new symbols created in *LTspice xvii* are shown. These are designed in consideration and in reference to the actual symbols found in the data sheets for each component. Figure 12 shows a picture over the resulting wiring diagram, a more comprehensive picture can be seen in Appendix B.

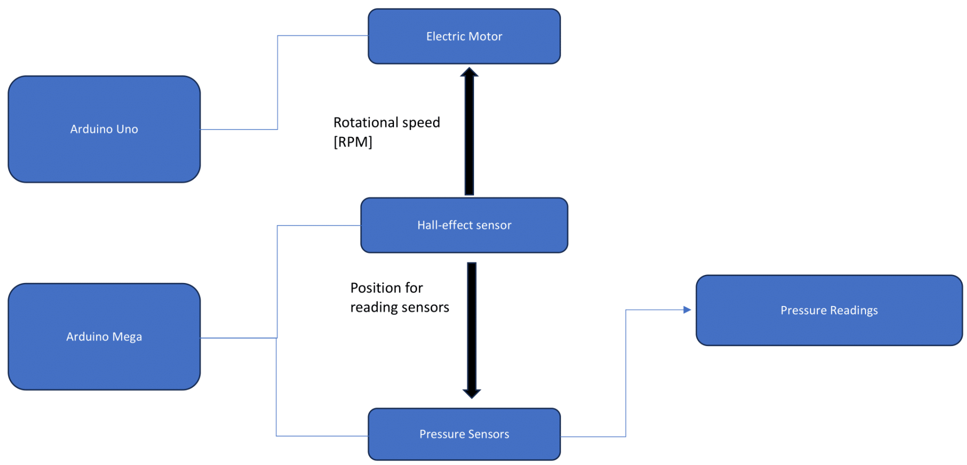
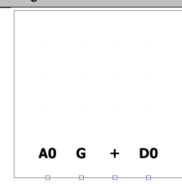
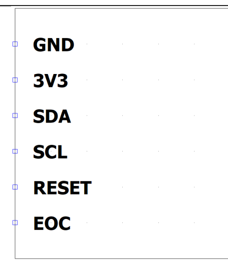
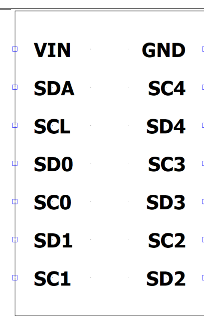
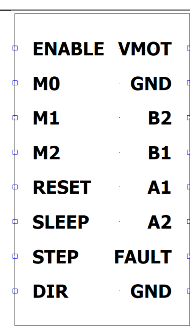


Figure 11: A schematic picture over the structure for the code controlling the system. This is implemented using Arduino IDE and the complete code can be found in Appendix A.

The wiring made in *LTspice xvii* is shown in the figure below.

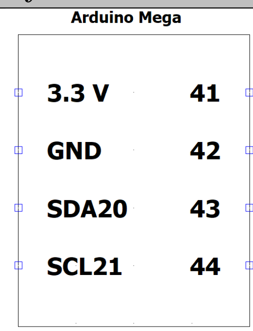
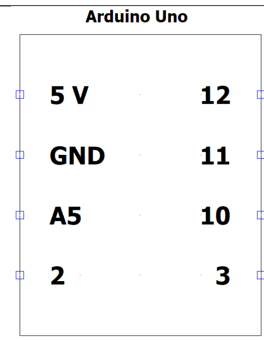
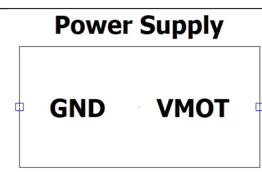
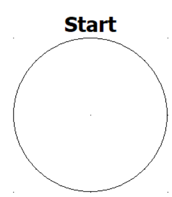
Table 4: *A table showing the symbols for the wiring diagram from those made in LTspice xvii.*

<table>
<tr><th>Component</th><th>Symbol created in LTspice xvii</th></tr>
<tr><td>Hall effect sensor</td><td>
</td></tr>
<tr><td>Sparkfun Micropressure</td><td>
</td></tr>
<tr><td>I2C Multiplexer</td><td>
</td></tr>
<tr><td>Stepper motor driver DRV8825</td><td>
</td></tr>
</table>

5.6 Control system

No control system was able to be implemented in this version of the GREC, however the system is design in such a way that it allows for a rather rapid implementation if to be desired in the future. This was mainly due to a limitation of time.

Table 5: *A continuation of table 3 showing the symbols for the wiring diagram designed out from those made in LTspice xvii.*

Component	**Symbol created in LTspice xvii**
Arduino Mega 2560	
Arduino Uno	
Power Supply	
Start button	

5.7 Testing

During testing it was discovered that the friction inside the GREC was not negligible as had been presumed. This resulted in the stepper motor not being able to actuate the RS.

This will be more extensive as the GREC and its electrical system is tested more.

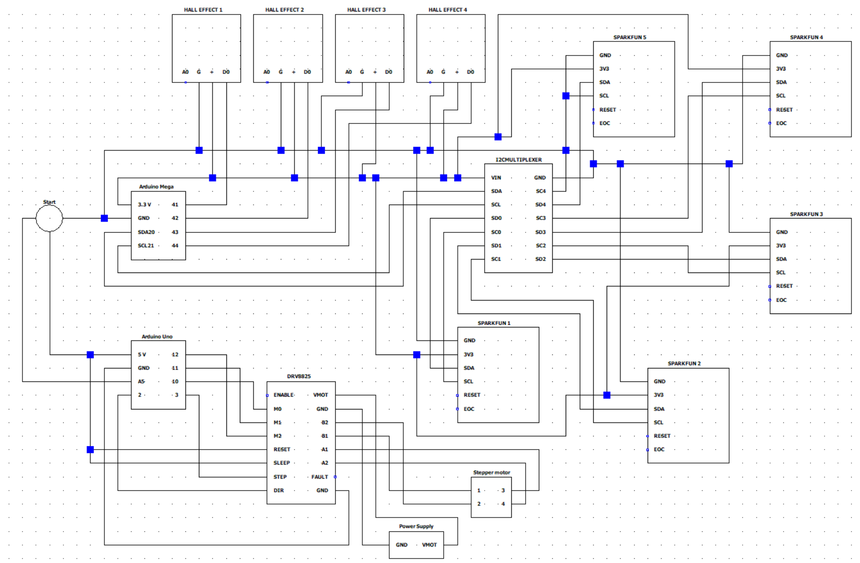


Figure 12: Figure showing the wiring diagram designed of the components for the GREC. For a clearer picture, see Appendix B

5.7.1 Mock-up

Before assembling the sensors on the actual GREC, a test assembly was designed. It was assembled on a wooden plate where a RS was drawn to illustrate the placement of the sensors as well as the cables. The sensors were taped to the plate whereas the sensors will actually instead be screwed into the GREC in places where the have been made adjustment in the design compared to the original to fit them. To simulate the RS moving in the mock-up, a magnet was moved from sensor to sensor and checked if it registered on the computer. In figure 13 the test assembly is shown.

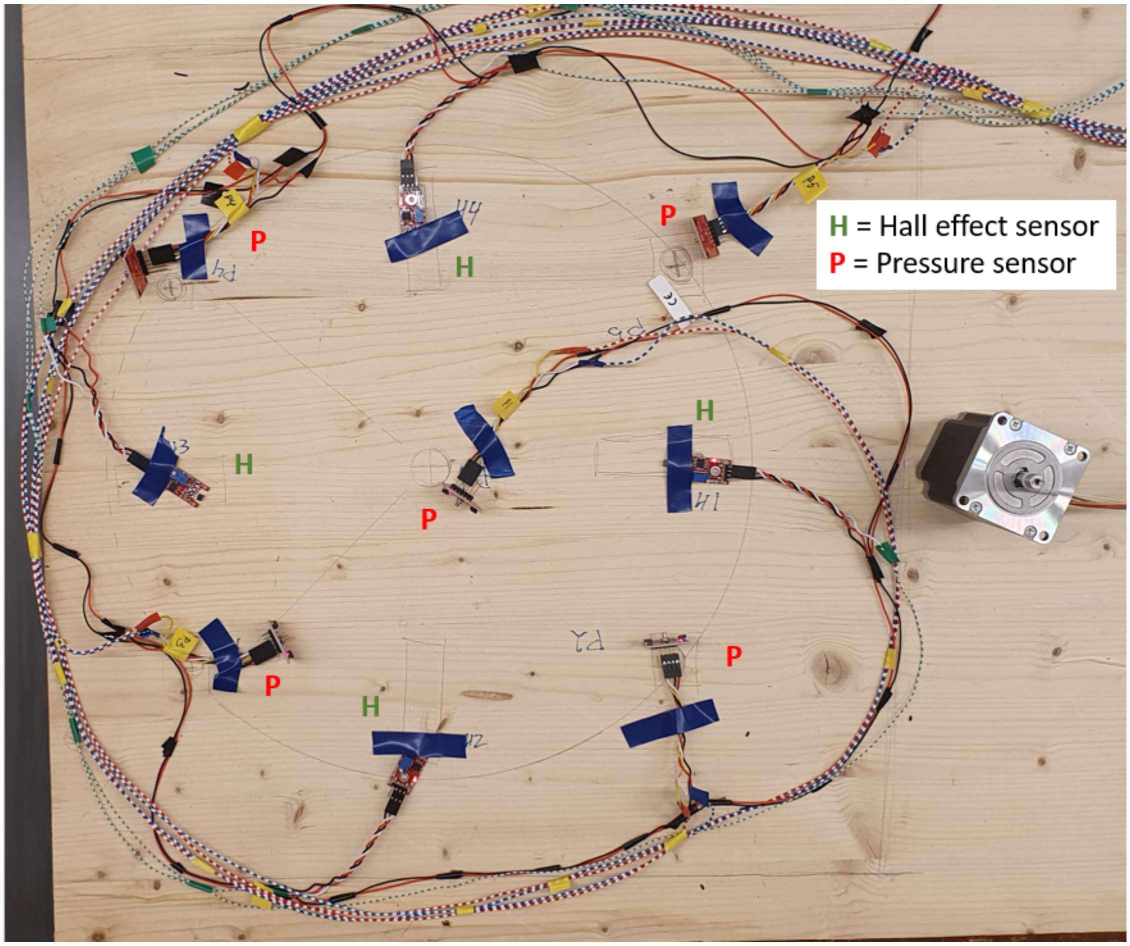


Figure 13: A test assembly of the approximate placement of the sensors in the GREC. A drawn RS is shown on a wooden plate to illustrate where the sensors are placed.

6 Discussion

In this section, results, the method, the references as well as some improvements and future work will be discussed.

6.1 Result discussion

Sensors
In general sensors that fit our desired requirements could be found. The only sensor that we had to skip for this project was the temperature sensors, this had to be skipped due to the characteristics of the temperature sensors in our price range. In general it could be said that this type of sensors has a slow measuring frequency, around 1 Hz, which is directly related to the fundamental principal of how they work. There are sensors to measure temperature on the market that has a higher update frequency, but these cost a lot due to the usage of more expensive material. Besides the current temperature inside the WGV, the temperature could be measured in only the cooling and heating flanges, but in order to do this a groove has to be milled into the aluminium. This way of measuring temperature however could interfere with the overal goal with the GREC and to not risk getting good results. Instead of measuring the temperature using sensors, the temperature of the flanges will be measured using a thermal camera in order to know what the highest and lowest temperature achieved is in the flanges.

The sensor used for measuring the speed and position (Hall sensors) works by detecting a magnetic field. This results in a somewhat limitation in what materials that can be used for the GREC. If any kind of magnetic material is nearby the sensor, the sensitivity for the sensors can be altered and thereby interfere with the result and efficiency of the sensors. These sensors also require a magnet to be mounted on the RS. This can cause some imbalances in the rotation that at higher speeds can lead to vibrations.

The group were able to find pressure sensors that met all of the requirements that the group had. However, the sensors could have been more easy to mount. The sensors that were decided on had a long port for measuring pressure, making it easy to mount the sensor and still making it airtight. This however made the sensor prone to breaking off from the board. A possible improvement could have been to choose sensors that are mounted by threading the whole sensor into the assembly. Since these had a higher price, the budget did not allow this at the time being, this could however be a future development for the GREC.

The GREC can cause a pretty rough environment for the sensors due to temperature. The sensor can be exposed to temperatures between -10 °C and +300 °C, this have to be taken in to account, and even though it is not something that we directly had as an requirement, it was taken into consideration if it was possible. We did not use the temperature as a requirement since the group decided that the other requirements had to be fulfilled first, and if the sensors measurements drift due to temperature, the temperature in the heating source can simply be turned down to determine if the temperature causes the issues.

The chosen **electric motor** performs somewhat as expected. It can accelerate up to 500 RPM without problem. However it can not start at 500 RPM(about 1666 pulses per second) since it has a maximum self start frequency of about 1500 pulses per second, so it needs to accelerate up to the desired speed especially if it is experiencing a load like the RS. During testing we discovered that if the motor spins slowly it requires more current than at high speeds and this will result in the motor not spinning at low speeds if it is not supplied with enough current. Likewise it has requirements for the voltage, only it's reversed, where it needs more voltage the faster it rotates. The motor is however more powerful than it needs to be but this was intentional since it was more important to get the GREC to rotate rather than to minimize the power supplied to make it rotate. Since this is a prototype meant for further research it was simpler to have more power than needed. In case of any friction coming into play as a result of this it's better to have an oversized motor to push past the friction. However since the main purpose of the GREC is to produce more energy than the motor consumes it will be important to optimize the electric motor in the future.

The motordriver DRV8825 is capable of running the motor however the power consumed by the motor heats it up fairly quickly. The motor runs on 24 VDC which means that the motor driver only supplies 2,5 A. The motor requires up to 6 A depending on the speed and load.

With the new GREC prototype the friction was a bigger problem than we expected. This resulted in the RS not to rotate as freely as we anticipated (and assumed it would) causing the stepper motor to skip steps. If we were to reconsider the type of electric motor with this information, there could have been an other outcome. This is because stepper engines are good if the friction is consistent, but not optimal when the friction is unpredictable.

Control System

As the results states the use of a control system was not implemented in this version but it is planned for. A feedback control system would be a great way to counter any unexpected friction that slows the RS down. A perk of using a stepper motor is that it is quite easy to control the RPM since the steps of the motor correspond to a certain degree of rotation. However, it have become obvious during previous projects that it is hard to design a system that is completely free from friction, and this friction can result in skipped steps. This basically means that the electric motor looses the sense of where the RS is compared to the starting point. If a control system was to be implemeted, not only could such a loss in rotation be countered, but also a more clear picture of where improvements to the design of the GREC is required, since the location of the friction can be monitored and also logged.

6.2 Method discussion

The method used for choosing the sensors worked quite well. The thing that took the longest time was to define the parameters properly before buying the sensors. In the beginning of looking at data-sheets for the different sensors the biggest hiccup was that the pressure sensors that seemed the most suitable only had a measuring range of a couple of kPa above atmospheric pressure. So we had to find a new candidate, which was the one ultimately chosen, where the difference in cost between them was almost double but compared to the whole budget it was a paltry sum. A problem we ran into later with the pressure sensors was that to be able to read the sensors using an Arduino we had to use the I2C protocol, which the Arduino only has 2 connections for. Since we planned on using five pressure sensors this didn't add up. We were also afraid that since all the sensors were identical they would have the same I2C address so that even though we used five sensors the Arduino might only detect one address. But we quickly found an I2C multiplexer which could collect the signals from all the different pressure sensors and assign a different address for each of them. So in the end we ended up with 5 pressure sensors which measure the pressure around the shell and an I2C multiplexer to split the signals.

For the position sensors we decided from the start to essentially copy the previous GREC prototypes system and use Hall effect sensors to detect a magnet on the RS. This has the advantage of being able to detect the position of the RS with the GREC completely sealed since the hall senors can detect magnetic fields through solid objects. The hall sensor modules chosen were also very cheap and easy to use so it was an obvious choice.

When choosing the micro-controller we went with an Arduino, and since we knew we would use several sensors we decided to use an Arduino Mega since it has more connection ports than the smaller Arduino Uno. What we later found out though was that Arduino Mega only has a single processor core so it can only so one function at a time. This led to problems with running the Stepper-motor in the same code that read the sensors. Even though the sensor readings only took a very small fraction of a second it was enough to disturb the motor code and resulted in that each time the sensor code ran the motor either slowed down or would stop the motor from running at all. To solve this problem we decided to use an Arduino Uno to only run the stepper-motor code and to have the sensor code on the Arduino Mega. This is contrary to what we had planned since we wanted to keep the micro-controller and wiring as compact and simple as possible, but we had to compromise to get the motor to actually rotate properly.

The assumption that the GREC would have no friction internally was not realistic. Even though there was not a lot of friction it was enough to stop the stepper motor in the early stages of testing. The tolerances inside the GREC were probably too tight and resulting in the fins clamping down on the RS and acting as a brake. When the fins were separated by the silicone sealant the RS could spin more freely inside the Engine, although it does scratch against the fins sometimes. The small amount of friction resulting from this scratching can be overcome with the chosen motor. However having the RS spin closer to the fins or if it were to wobble too much it might result in too much friction and the subsequent stopping of the motor.

6.3 Reference discussion

For the theory chapter containing previous work and the background of the GREC, the website of the inventor and creator of GREC - nilsinside AB - was used, as well as the two reports from previous work made on the GREC at Linköping University. For more information, a few meetings with the creator of GREC was also held so that a better understanding of the concept could be achieved. For research regarding the sensors and electric motor, different data sheets on the websites such as Elfa and Electrokit were used. The parameters that were researched on the data sheets were decided from the sensors previously used and calculations made by previous work as well as for this project. In addition to the data sheets, research was also made for the different types of sensors and motor that could be used. This research was made with different websites, all of which are referred to in the reference chapter.

6.4 Improvements & Future Work

The findings and limitations of the project points on some clear improvements that can be made for the future in order to create an even more sound and more effective system that can controlled to a greater extend.

The first improvement that the system that this project resulted in is to change the controller for the motor to a controller that can be more easily controlled. The current one only allows for an output of 2 Ampere and in order to match the motor better. This however is, at the time writing, expensive and would require the budget to be extended.

Micro controller considerations: another improvement that can be made is to reconsider the choice of micro controller. The system works using two Arduinos, which is not optimal since this results in a lot of messy wiring, different programs have to be written and implemented. To make this a better system, future work should focus on using only one micro controller that can carry out multiple tasks at once, this would allow the whole GREC to be controlled by the same computer.

Temperature measurements: This project looked in to different methods to measure temperature and came to the conclusion that it would not be a good decision to try to measure the temperature of the air in the WGV. This was due to the fact that temperature sensors due to how they work can not update at a high enough frequency. Future work should look in to the possibility to include temperature sensors in the heating and cooling fins as well as the neutral fins.

Due to lack of time, implementation of a control system was not possible. This is however planned for and should not be a too big of an effort to do in the future in order to be sure that the GREC actually spins at the expected RPM

Another aspect that future projects can take in to consideration is to measure the ambient pressure in order to get a better understanding of how much work can actually be put, since the pressure difference between the hot and cold side is not only important, but also the difference in pressure between the ambient pressure and the pressure inside of the GREC.

7 Conclusion

This project set out to explore the effects of electric motor selection, microprocessor choice, and sensor selection on the performance of the Green Revolution Energy Converter (GREC). From the projects result, we can draw the following conclusions regarding the research questions.

RQ1. What factors should be considered when selecting an electric motor and driver for the GREC? The chosen electric motor performed as expected, being able to accelerate up to 500 RPM without issues. However the motor driver was under-powered, thus limiting the torque of the electric motor. This leads to the conclusion that when choosing a motor, one has to consider a lot of aspects. To dimension a motor and a driver for the GREC engine is a hard task, but with the knowledge gained from this project, we have a better understanding of unexpected factors and how they can impact the selection of an electric motor.

RQ2. How does the choice of microprocessor influence the capability of the GREC motor? The choice of microprocessor, in this case, an Arduino Mega, had limitations in terms of running multiple functions simultaneously. Running the sensor code and motor code on the same Arduino caused disturbances in motor operation. To resolve this issue, an Arduino Uno was used to run the stepper-motor code separately. This limits the GREC in some aspect, since the Arduinos do not communicate with each other. However, this can be solved using I2C comminication between the units.

RQ3. In what way does the choice of sensors alter the quality of the measurements for the GREC? The selection of sensors played a crucial role in obtaining accurate measurements for the GREC. Pressure sensors were chosen successfully, meeting all requirements. However, since all of these had the same I2C adress, a multiplexer had to be used which slowed down the reading time. In other words, the pressure sensors have the required resolution and measuring frequency, however the I2C communication haltered this. Temperature sensors were skipped due to their slow measuring frequency and potential interference with the GREC's overall goal. Temperature of the fins could have been measured to complement the measurements of pressure and get a better understanding of the efficiency of the GREC.

In conclusion, the selection of electric motor, microprocessor, and sensors has significant implications for the performance of the GREC. Future improvements should focus on optimizing the electric motor for both performance and also power consumption, reconsidering the microcontroller choice for better control, and exploring temperature measurements in various areas of the GREC.

References

[1] Nils Karlberg. *What is this Green Revolutionary news about?* URL: https://nilsinside.com/. (accessed: 02.03.2023).

[2] H. Turner R A. Cengel Y Cimbala J. *Fundamentals of Thermal-Fluid Sciences*. 5th ed. McGraw-Hill Education, 2005.

[3] Markus Eriksson. Oscar Magnusson. Lukas Haglund. John Malmdal. Gustav Edholm. *Theoretical Proof Of Concept For The Green Revolution Energy Converter*. Tech. rep. ———. Mar. 2022.

[4] Johan Hagströmer. Mattias Reijm. Oscar Torsteinstrud. Vendela Stenholm. *Investigation of the internal heat transfer in GREC*. Tech. rep. ———. Jan. 2023.

[5] *Electric Motors and Drivers*. URL: http://www.emic-bg.org/files/Electric_Motors___Drives.pdf. (accessed:05:04:2023).

[6] Hughes A. *Electric Motors and Drivers*. 3rd ed. Oxford: Elsevier, 2006.

[7] *Stepper Motor Working Principle*. URL: http://www.robotpark.com/Stepper-Motor-Working#:~:text=Half. (accessed: 24:04:2023).

[8] *Microstepping Myths*. URL: https://www.machinedesign.com/archive/article/21812154/microstepping-myths. (accessed:25:04:2023).

[9] *How Do Temperature Sensors Work?* URL: https://atlas-scientific.com/blog/types-of-pressure-sensors/. (accessed: 04.04.2023).

[10] *A Silicon Piezoresistive Pressure Sensor*. URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=994611. (accessed: 18:04:2023).

[11] *Everything You Need To Know About Hall Effect Sensors*. URL: https://se.rs-online.com/web/generalDisplay.html?id=ideas-and-advice/hall-effect-sensors-guide. (accessed: 20:04:2023).

[12] *Response Time Considerations in Temperature Sensing*. URL: https://www.minco.com/wp-content/uploads/Minco-Time-Constant-Considerations-Sensors-Whitepaper.pdf. (accessed:20:04:2023).

[13] Ljung L Glad T. *Reglerteknik : grundläggande teori*. 4th ed. Lund: Studentlitteratur, 2006.

[14] *Ex2 - PID*. URL: https://people.kth.se/~laperss/assets/documents/EL1000/ex2_pid.pdf. (accessed:28:04:2023).

[15] *Arduino*. URL: https://www.arduino.cc/. (accessed:19:04:2023).

[16] *How I2C Communication Works? Arduino and I2C Tutorial*. URL: https://howtomechatronics.com/tutorials/arduino/how-i2c-communication-works-and-how-to-use-it-with-arduino/. (accessed:19:04:2023).

[17] *MPR Series*. 32332628. Issue F. Honeywell. 2019. URL: https://www.electrokit.com/uploads/productfile/41017/honeywell-mpr-datasheet.pdf.

[18] *Adafruit TCA9548A 1-to-8 I2C Multiplexer Breakout*. not available. Last updated 2016. Adafruit. 2016. URL: https://www.elfa.se/Web/Downloads/_t/ds/Adafruit_2717_eng_tds.pdf.

[19] *Linear Hall-effect Sensor ICs*. 005850-4-EN IL50. February. Honeywell. 2015. URL: https://www.mouser.se/datasheet/2/187/HWSC_S_A0012826248_1-3073340.pdf.

[20] *56 mm sq. 2-Phase Stepping Motors*. CATALOG No.S1056B001 '21.5. Motor model: SM2564C60B41. Sanyo Denki. 2017. URL: https://www.elfa.se/Web/Downloads/_t/ds/SM256_eng_tds.pdf.

[21] *DRV8825 Stepper Motor Controller IC*. SLVSA73F. REVISED JULY 2014. Texas Instruments. 2010. URL: https://www.electrokit.com/uploads/productfile/41016/drv8825.pdf.

[22] Microsoft. *Enable the Data Streamer add-in*. URL: https://support.microsoft.com/en-us/office/enable-the-data-streamer-add-in-70052b28-3b00-41e7-8ab6-8a9f142dffeb. (accessed: 02:05:2023).

A Appendix A

Code for running the stepper

```
#include <AccelStepper.h>  //Import needed library in order to accelerate the stepper motor
#define MOTOR_A_ENABLE_PIN 4 //Define the pins of the motor
#define MOTOR_A_STEP_PIN 3
#define MOTOR_A_DIR_PIN 2

// Define a stepper and the pins it will use
AccelStepper stepper(1, MOTOR_A_STEP_PIN, MOTOR_A_DIR_PIN);

int M0 = 10;  //Define pins for microstepping, only M0 high will result in 1/2 step
int M_1 = 11;
int M_2 = 12;

int targ = 1000000000; //set a target that the stepper moves to, make this really high,
                       //or set a distance in order to make it go to a specific point.

void setup() {
  // Set up for the motor, and also the button that starts the motor
  pinMode(A5, INPUT_PULLUP);
  pinMode(M0, OUTPUT);
  pinMode(M_1, OUTPUT);
  pinMode(M_2, OUTPUT);
  stepper.setMaxSpeed(3000);
  stepper.setAcceleration(200);
}

void loop() {
  digitalWrite(M0, HIGH); //define what kind of microstepping that is used
  digitalWrite(M_1, LOW);
  digitalWrite(M_2, LOW);

  if (digitalRead(A5) == HIGH)  // if statement that checks if the button is activated,
                                //if activated the motor will go to a target distance
  {
    stepper.moveTo(targ);
  }
```

Code for reading sensors

```
/*Include the needed libraries*/


#include <Wire.h>
#include <SparkFun_MicroPressure.h>

/* delay without delay*/

float previousMillis1;


/* Pressure Sensors, defining the different sensors and the pressures*/

SparkFun_MicroPressure mpr1;
SparkFun_MicroPressure mpr2;
SparkFun_MicroPressure mpr3;
SparkFun_MicroPressure mpr4;
SparkFun_MicroPressure mpr5;

float tryck1;
float tryck2;
float tryck3;
float tryck4;
float tryck5;


//The following code defines the different SDA and SCA ports on the multiplexer
#define TCAADDR 0x70
void tcaselect (uint8_t i) {
  if (i > 7) return;

  Wire.beginTransmission(TCAADDR);
  Wire.write(1 << i);
  Wire.endTransmission();
}


//The following values declare the values and pins are relevant for the Hall sensors
int hall_1 = 41; //sensor pin
int hall_2 = 42; //sensor pin
int hall_3 = 43; //sensor pin
```

```
int hall_4 = 44; //sensor

int val_1; //numeric variable
int val_2; //numeric variable
int val_3; //numeric variable
int val_4; //numeric variable

int old_val_1;
int old_val_2;
int old_val_3;
int old_val_4;

//Timing variables
float start_time1;
float start_time2;
float start_time3;
float start_time4;

float end_time1;
float end_time2;
float end_time3;
float end_time4;

float time_passed1;
float time_passed2;
float time_passed3;
float time_passed4;

float rpm1;
float rpm2;
float rpm3;
float rpm4;

int TC=15; //Time constant for use


/*SETUP */


void setup() {
  Serial.begin(115200);        //START THE SERIAL COMMUNICATION
```

```
Wire.begin();              //BEGIN THE WIRE COMMUNICATION IN ABLE TO BE ABLE
                          //TO READ SENSORS OVER I2C
Wire.setClock(3400000);  //SET THE CLOCKSPEED FOR THE WIRE COMMUNICATION
//*************INITIALIZING FIRST SENSOR******************************
tcaselect(0);
if (!mpr1.begin())
{ Serial.print(F("Micropressure Nr.1 detected?\t")); Serial.println(F("No")); }
else
{ Serial.print(F("Micropressure Nr.1 detected?\t")); Serial.println(F("Yes")); }
//*****************************************************************


//*************INITIALIZING SECOND SENSOR******************************
tcaselect(1);
if (!mpr2.begin())
{ Serial.print(F("Micropressure Nr.2 detected?\t")); Serial.println(F("No")); }
else
{ Serial.print(F("Micropressure Nr.2 detected?\t")); Serial.println(F("Yes")); }
//*****************************************************************

  //*************INITIALIZING THIRD SENSOR******************************
tcaselect(2);
if (!mpr3.begin())
{ Serial.print(F("Micropressure Nr.3 detected?\t")); Serial.println(F("No")); }
else
{ Serial.print(F("Micropressure Nr.3 detected?\t")); Serial.println(F("Yes")); }
//*****************************************************************

  //*************INITIALIZING FOURTH SENSOR******************************
tcaselect(3);
if (!mpr4.begin())
{ Serial.print(F("Micropressure Nr.4 detected?\t")); Serial.println(F("No")); }
else
{ Serial.print(F("Micropressure Nr.4 detected?\t")); Serial.println(F("Yes")); }
//*****************************************************************


 //*************INITIALIZING Fifth SENSOR******************************
tcaselect(4);
if (!mpr5.begin())
```

```
  { Serial.print(F("Micropressure Nr.5 detected?\t")); Serial.println(F("No")); }
  else
  { Serial.print(F("Micropressure Nr.5 detected?\t")); Serial.println(F("Yes")); }
  //*****************************************************************

      //Hall Sensors
        pinMode(hall_1, INPUT); //set sensor pin as input
        pinMode(hall_2, INPUT); //set sensor pin as input
        pinMode(hall_3, INPUT); //set sensor pin as input
        pinMode(hall_4, INPUT); //set sensor pin as input
}


/* LOOP */


void loop() {

    //Code to read and print the values of the sensors


    if(millis() - previousMillis1 > 10){
      //this is used in order to delay the code, without actually using delays,
     //since that stops the code for the duration of the delay...

    val_1 = digitalRead(hall_1); //Read the sensor
    if (val_1 != old_val_1){  //See if the value changes, if it changes to 0 it turns off,
      old_val_1=val_1;       //1 if it turns on save the new value for comparison
                            //when the code loops.

      if(val_1==HIGH){         //if the value changes and it changes to the "on" position,
                              //the timer starts
        //read pressure sensor
        start_time1 = micros();  //Starts counting microseconds between Hall 1 and 2
        end_time4 = micros();   //Measures the time since Hall 4 was triggered.
           time_passed4 = (end_time4-start_time4)/1000000.0; //Divide by 1 mil since it is
                                                         //measured in microseconds
           rpm4=TC/time_passed4;  //calculate RPM
           time_passed4=0;       //Reset the "laptime" between Hall 1 and 4
           Serial.print("1, ");
           Serial.print(rpm4);
```

```
       tcaselect(0);
          tryck1 =  mpr1.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck1);

          tcaselect(1);
          tryck2=mpr2.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck2);

          tcaselect(2);
          tryck3=mpr3.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck3);


          tcaselect(3);
          tryck4=mpr4.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck4);

          tcaselect(4);
          tryck5=mpr5.readPressure(PA);
          Serial.print(", ");
          Serial.println(tryck5);
     }
    }
//The code above is reused with the only changes being to target the correct Hall sensor

    val_2 = digitalRead(hall_2);
    if (val_2 != old_val_2){
      old_val_2=val_2;

      if(val_2==HIGH){
        start_time2 = micros();
        end_time1 = micros();
           time_passed1 = (end_time1-start_time1)/1000000.0;
           rpm1=TC/time_passed1;
           time_passed1=0;
          Serial.print("2, ");
```

```
         Serial.print(rpm1);

      tcaselect(0);
          tryck1 =  mpr1.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck1);

          tcaselect(1);
          tryck2=mpr2.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck2);

          tcaselect(2);
          tryck3=mpr3.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck3);

          tcaselect(3);
          tryck4=mpr4.readPressure(PA);
          Serial.print(", ");
          Serial.print(tryck4);

          tcaselect(4);
          tryck5=mpr5.readPressure(PA);
          Serial.print(", ");
          Serial.println(tryck5);
   }
  }

val_3 = digitalRead(hall_3);
  if (val_3 != old_val_3){
    old_val_3=val_3;

      if (val_3 == HIGH){
          start_time3=micros();
          end_time2 = micros();
         time_passed2 = (end_time2-start_time2)/1000000.0;
         rpm2=TC/time_passed2;
         time_passed2=0;
         Serial.print("3, ");
         Serial.print(rpm2);
```

```
        tcaselect(0);
         tryck1 =  mpr1.readPressure(PA);
         Serial.print(", ");
         Serial.print(tryck1);

         tcaselect(1);
         tryck2=mpr2.readPressure(PA);
         Serial.print(", ");
         Serial.print(tryck2);

         tcaselect(2);
         tryck3=mpr3.readPressure(PA);
         Serial.print(", ");
         Serial.print(tryck3);

         tcaselect(3);
         tryck4=mpr4.readPressure(PA);
         Serial.print(", ");
         Serial.print(tryck4);

         tcaselect(4);
         tryck5=mpr5.readPressure(PA);
         Serial.print(", ");
         Serial.println(tryck5);
     }
}

  val_4 = digitalRead(hall_4);
 if (val_4 != old_val_4){
   old_val_4=val_4;


   if(val_4==HIGH){
         start_time4=micros();
         end_time3 = micros();
        time_passed3 = (end_time3-start_time3)/1000000.0;
        rpm3=TC/time_passed3;
        time_passed3=0;
        Serial.print("4, ");
        Serial.print(rpm3);
```

```
          tcaselect(0);
           tryck1 =  mpr1.readPressure(PA);
           Serial.print(", ");
           Serial.print(tryck1);

           tcaselect(1);
           tryck2=mpr2.readPressure(PA);
           Serial.print(", ");
           Serial.print(tryck2);

           tcaselect(2);
           tryck3=mpr3.readPressure(PA);
           Serial.print(", ");
           Serial.print(tryck3);

           tcaselect(3);
           tryck4=mpr4.readPressure(PA);
           Serial.print(", ");
           Serial.print(tryck4);

           tcaselect(4);
           tryck5=mpr5.readPressure(PA);
           Serial.print(", ");
           Serial.println(tryck5);
    }
   }

       previousMillis1 = millis();

     }
}
```

B Appendix B

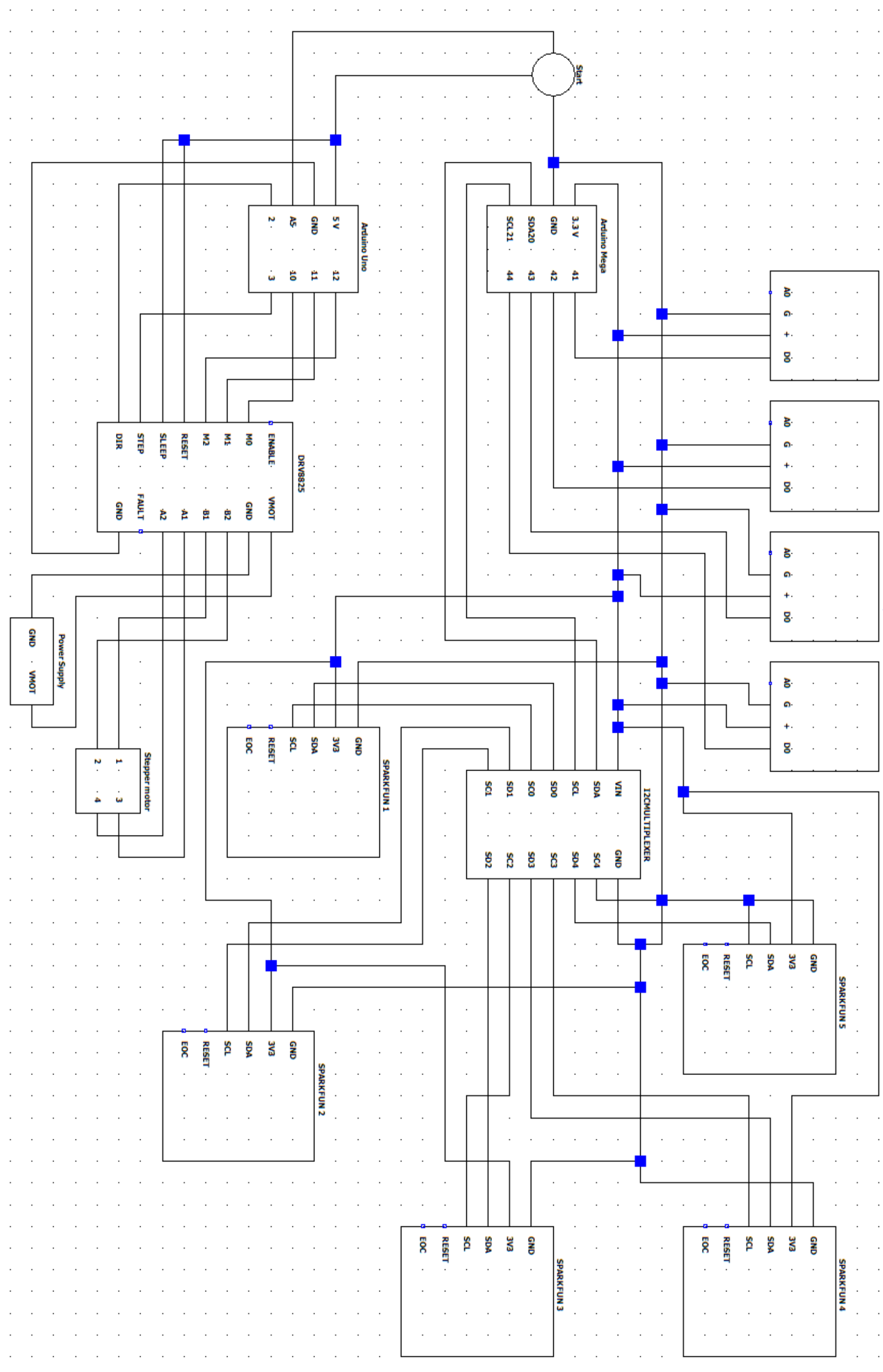


Figure 14: Wiring diagram for the GREC.