Microfluidics system for the MOREBAC astrobiology experiment module

Design of a cubesat module

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Abstract

In order for humans to travel further into space, spacecrafts must be able to sustain life for several months. One way to do this is to have a biological life support system containing bacteria to provide the necessary eco-system to support life. The aim of MOREBAC is to evaluate whether it is possible to resurrect these kinds of bacteria while in space and after several months in a freeze dried state. MOREBAC will be one of several experiments onboard the CubeSat MIST, and will be the smallest experiment of its kind to be executed in orbit.

This project focused on the resurrection and keeping the bacteria alive for the experiment period, which includes fluid actuation of nutrient, pressure- and temperature control of the bacteria environment. A prototype of the system was designed, built and tested to evaluate whether the techniques used are suitable for a space mission. It was deemed that the design was a valid option but several suggestions for improvements were also given.
Sammanfattning

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Mikrofluidiksystem för astrobiologimodulen MOREBAC

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För att möjliggöra rymdresor med människor till mer avlägsna platser än tidigare måste rymdfarkosterna bibehålla liv i flera månader. Ett sätt att lösa detta är att ha biologiska livsupphållande system som med hjälp av bakterier tillför och omvandlar de nödvändiga faktorena för liv. Målet med MOREBAC är att utvärdera huruvida det är möjligt att återuppliva den typen av bakterier från frystorkat tillstånd, efter en längre tid i rymden. MOREBAC kommer vara en av ett flertal experiment som är en del av kubsatelliten MIST, och kommer bli det minsta biologimodul experimentet av sitt slag som utförs i omloppsbana.

Det här projektet fokuserade på designen av systemen som ska kontrollera miljön kring bakterierna, via aktivering av näringssvätksa, tryck- och temperaturreglering. En prototyp av experimentet designades, byggdes och testades för att utvärdera dess förmåga att återuppväcka bakterierna. Prototypen ansågs vara tillräckligt utvecklad för att klara uppgiften, men med ett flertal forslag på förbättringar för den slutgiltiga konstruktionen.
Acknowledgments

The authors would like to thank Håkan Jönsson as he has been the driving force behind MOREBAC and has supervised the project. But MOREBAC would not be possible without the host satellite MIST. Sven Grahn is responsible for MIST and has also provided input to the project, mainly regarding requirements on the satellite as a whole and the temperature system. Without Sven there would have been no MOREBAC or MIST. From the Mechatronics faculty Mikael Hellgren has supervised the thesis project. The authors would like to thank Mikael for his feedback throughout the project. Lei Feng was the examiner of the thesis and his feedback to the overall quality of the report was greatly appreciated.
# Contents

Acknowledgments v

List of Figures ix

List of Tables x

1 Introduction 1

1.1 Background ........................................ 1
1.2 Purpose and Problem description ................... 2
  1.2.1 Purpose of thesis ............................. 2
1.3 Research Questions .................................. 2
1.4 Scientific Methodology ............................. 3
1.5 Delimitations ...................................... 3
1.6 Changes along the way ............................. 3
1.7 Division of Work .................................. 4
1.8 Ethics ............................................. 4
1.9 Economical Aspects ............................... 5

2 Background 7

2.1 Cube Satellites ..................................... 7
2.2 MIST ............................................. 8
2.3 Micro Fluidics ..................................... 9
2.4 Life Support Systems and Bacteria ................ 9
2.5 NASA’s Biology cube satellites .................... 10
  2.5.1 GeneSat-1 ..................................... 10
  2.5.2 PharmaSat ..................................... 12
  2.5.3 O/OREOS ..................................... 13

3 Review of Space Fluid systems 15

3.1 Reservoir and Pressurization ....................... 15
3.2 Fluidic Routing System ............................ 16
3.3 Temperature System ................................ 17

4 System Design 19


List of Figures

2.1 Mist satellite without side solar panels. MOREBAC is the dark blue box on the top 1U .................................................. 8
2.2 GeneSat-1 Fluidics Card [10] ........................................... 10
2.3 Exploded view of GeneSat-1 Fluid Reservoir [21] .................... 11
2.4 Fluidics card temperature after activation of the system. Average temperature from 6 sensors. [19] ................................. 11
2.5 Cross section of PharmaSat Fluidics card [20] ....................... 12
2.6 Temperature profile for SESLO [12] .................................. 14
3.1 Block Diagram of PharmaSat Fluidics card .......................... 17
4.1 Exploded CAD render of MOREBAC and its components. Front and side view ......................................................... 19
4.2 Block diagram of the fluidic dosing system, the 4 three way valves direct the fluid to the correct bacteria wells and the filters keep the bacteria inside the wells ...................................................... 21
4.3 CAD render of the fluidics card and its components .................. 22
4.4 CAD render of the nutrient bag and its pressure construction ...... 23
4.5 Cross section of fluidics card with inlet and outlet to the culture wells . 24
4.6 Exploded view of Fluidics Card .......................................... 26
5.1 Logic within statechart for three-way valve ............................ 32
5.2 Model for well fill-up process simulation .............................. 33
5.3 Results from simulation .................................................... 33
5.4 Representation of the view factor [26] .................................. 36
5.5 Two opposite, rectangular and same sized surfaces [26] ............. 36
7.1 Power to heaters plotted against time required to heat the experiment during cold case operational ......................... 44
B.1 Fluidic system ............................................................ 54
C.1 List of components that are bought for MOREBAC ................. 58
D.1 Electric Schematic ....................................................... 59
List of Tables

4.1 Valve material and acceptance status ........................................... 24
4.2 Power consumption per component ............................................... 28

5.1 Tables of variables and their definition from equation of conduction losses. 34
5.2 Tables of variables and their definition from equation of radiation losses 34
5.3 Tables of variables and their definition from equation of heat capacity . 35
5.4 Power Consumption Variables .................................................... 37

6.1 Component Power Consumption ................................................... 40
6.2 Component Individual Masses ..................................................... 41
Nomenclature

Atm  Atmosphere (Pressure)
CAD  Computer Aided Design
ESA  European Space Agency
FEP  Fluorinated Ethylene Propylene
KTH  Royal Institute of technology
MELiSSA  Micro-Ecological Life Support System Alternative
MIST  Miniature Student SaTellite
MOREBAC  Microfluidic Orbital Resuscitation of BACteria
NASA  National Aeronautics and Space Administration
OBC  On-Board Computer
PCB  Printed Circuit Board
SESLO  Space Environment Survivability of Live Organisms
SEVO  Space Environment Viablility of Organisms
Chapter 1

Introduction

The goal of this thesis was to design and construct the fluid handling system for the biology-experiment module MOREBAC, which would be launched onboard the MIST (the Miniature Student SaTellite) satellite [22]. The MOREBAC experiment is a project from SciLifeLab (short for Science for Life Laboratory), a collaboration between the Karolinska Institute, Royal Institute of Technology (KTH), Stockholm University and Uppsala University. This chapter covers the background of the experiment, the purpose of the thesis and discuss the ethics of the project briefly.

1.1 Background

Biological life support systems (BLSS) are being developed at NASA and ESA for long term space missions. The objective of these efforts is to design a miniature eco-system to provide for human needs while in space. As part of this development microbial species for use in space have been tested on the ISS on a number of missions. Recently, miniaturization of fluidics and control electronics has made it possible to deploy such experiments on miniature satellites, possibly lowering cost and speeding the rate of development. The MOREBAC experiment, approved for deployment aboard the KTH Miniature student satellite (MIST) aims to further push the boundaries on miniaturization of biological experimentation in space by deploying multiple parallel bacterial culture experiments in orbit on strains intended for BLSS in a more miniaturized format than the two previous bacterial miniature satellite missions. It also aims to test whether bacteria can be transported in space in a freeze dried state and subsequently resuscitated after extended periods in space. One of the main challenges in achieving this will be to develop the fluid actuation, pressure sensing and control system for the MOREBAC experiment under the constraints imposed by operation on an orbiting mini satellite with a biological payload. Previous work on MOREBAC includes thermal analysis [1], light measuring equipment for measuring bacteria growth [2]. Therefore nothing was done in this area during the project.
1.2 Purpose and Problem description

The purpose of the MOREBAC experiment is to build a smaller experiment platform than earlier bacteria experiments in space, and to attempt resuscitation. This enables more bacteria experiments to be conducted and characterize bacteria resuscitation (which in turn allows further use of bacteria for space mission) due to decreased costs associated with space experiments.

1.2.1 Purpose of thesis

In order for a successful resurrection of the bacteria both pressure and temperature have to be controlled. Pressure and temperature are correlated so if both are controlled simultaneously they affect each other, this might cause further power demands. Power is a limitation and this might worsen control performance. Since magnetic emissions will affect the attitude of the satellite it is important to not exceed the limitations. This is important when choosing actuators, for example electric motors which have permanent magnets that cause disturbances at all times. Electric motors also emit electromagnetic disturbances due to varying currents in coils during operation. Therefore it was interesting to know how the controller can be designed with regards to the limited power.

Fluids (in this case water) behaves differently in free fall (micro-gravity) and this must be taken into consideration when designing the fluidics system. The ambient pressure can safely be assumed to be 0 (Bar, Atm). The low ambient pressure causes additional problems, one example being outgassing.

Therefore the purpose of the engineering task was to investigate how to build a fluidic system, capable of running a bacteria experiment in space, given the constraints from the satellite.

1.3 Research Questions

A crucial part of the MOREBAC experiment module is the fluid actuation system which purpose is to supply the bacteria with nutrient in order to resuscitate them. There are many ways this could be done, but with the constraints on space, power and the space environment itself, the design of the actuation systems becomes limited. Therefore it is important that the design is optimized with regards to the requirements of this experiment, see Appendix A. This leads to the research questions to be answered in this thesis.

- What are suitable fluid actuation techniques for space conditions? (micro-gravity, vacuum).
- How is rise time, of the temperature controller, affected by the power limitations of the system.
1.4 Scientific Methodology

A thorough literature study on previous work in this field was conducted in order to answer the first research question. Along with actual solutions to the question, related subjects were included in the study, such as out-gassing. The literature is mainly from NASA project reports on three similar biological experiments on miniature satellites, documentation for the MIST satellite, conferences and scientific reports. The goal was to gather knowledge on the design of previous experiments and by comparing them be able to draw conclusions on how MOREBAC was to be built.

One design out of many concepts was chosen for evaluation in this project. The evaluation was carried out in the form of a case study where the result was qualitatively evaluated. As the experiment will be run in space there are some factors that are difficult to evaluate here on earth, such as the effects of microgravity. Therefore one part of the scientific method was to theoretically evaluate whether the fluid actuation technique chosen is suitable for space conditions. This case study would be used to answer the second research question, while further reasserting the answer to the first question.

The literature study would give several answers about fluid actuation systems and only together with the case study on a specific system could the answer be validated (if only for the chosen design relevant for MOREBAC). Therefore the case study was to answer both research questions by experiments and evaluation. The components in the fluid actuation system could be tested and evaluated separately and by comparing them to performance of previous experiments and requirement compliance RQ1 could be answered.

The experiments used in the case study were designed to answer how well the system performed. It was desired to have effects from gravity negligible and this was assumed to be achieved by using small scale for all fluid volumes. When that is the case other effects such as surface tension are much bigger than the impact from gravity.

1.5 Delimitations

Since free fall tests are unfeasible or too expensive the module prototype will not undergo any low gravity test. Since the purpose of the thesis was to design and build the mechanical parts and related software, the purely biological related parts were not dealt with, for example sensor for detecting the bacterial growth. Therefore no experiment with bacteria will be conducted.

1.6 Changes along the way

During the project the priorities changed as work progressed. During the literature review and background study more focus was on the fluidics system and related
components such as valves. Later it was realized that the temperature part was too
critical not to be focused on as resources was reallocated to further progress the
work on temperature modeling and design of the system from a thermal point of
view. This was beneficial since more exact simulations of the fluidics components
was deemed unnecessary.

The project was carried out using a v-model approach. Specifying system level
requirements first to later step down in level and build and test parts of the system
to later be integrated to the module prototype. The changes of focus areas can be
seen as taking steps in the wrong direction of the development model, but this is
acceptable since the idea of the v-model is to allow reiterations before work has
gone too far.

1.7 Division of Work

The background and literature study was a collaboration between both Aron and
Alexander. Both needed a solid base of knowledge to continue the work. The system
design was divided into smaller parts. Alexander did the layout of the fluidics card,
placing wells and fluid channels, which Aron modeled in CAD software. Alexander
was responsible for the valves and H-bridge while Aron looked into sensors and i2c
multiplexer. For the software and simulation part Aron did the thermal analysis,
while Alexander did Simulink implementation of the system, both sensors and other
electronics. The PCB design was done collaboratively since it included both sensors
and valve actuation electronics. All components and designs within this project was
selected by the writers.

1.8 Ethics

The project follows KTH’s ethical guidelines [7]. This thesis does not handle any
bacteria, and therefore no bacteria will “die”.

The long term goal of the bacteria experiments is to be able to transport bacteria
to create new ecosystems on other terrestrial objects, for example Mars. Colonizing
Mars has the risk of killing all living things, if any, that is native on the planet. If
Mars is barren we do not see this infestation of bacteria as a problem, furthermore
it can be of benefit to humanity.

If transportation of bacteria will be feasible then it can also be applied for human
space travel. The bacteria can then support life systems on the vessel, and be kept
as a back up in case of failure of the spaceships current micro-ecosystem. Mistakes
and unbalance in the life support systems can lead to the astronaut’s death, making
them critical for any manned mission in space of considerable length.

MOREBAC’s scope is not this grand and the bacteria will be contained on the
CubeSat until it deorbits and burns up during reentry. The bacteria used will be
single cell organisms, probably some sort of yeast. These are not aware organisms,
and therefore it is assumed they can not suffer and do not feel pain. The systems
that are being developed are supposed to resurrect simple organisms that support life for animals (and plants), never to resurrect animals themselves.

The idea of interplanetary travel and humans not living on earth is not new, and progress is being made fast in many of the required areas. It seems inevitable that someone will try to move humans to Mars permanently. To make these kind of missions viable in the long term life support systems must be thoroughly studied and being able to transport the required bacteria for these ecosystems is an important part of this research.

1.9 Economical Aspects

Outer space experiments was until a few years ago very expensive and difficult to achieve. The CubeSat industry allows universities and others to do research in space and microgravity with relatively cheap methods. As the CubeSat industry is growing there are more and more companies providing off-the-shelf products such as thrusters, structure, antennas etc, which even further cuts the cost of producing CubeSats since the developing costs are much less. The whole infrastructure of the CubeSat industry allows the CubeSats to be developed and launched quickly and inexpensively [25]. The cost of each component in this project can be seen in Appendix C, although it excludes the fluidics card and the PCB which are made in-house. As seen the components are relatively cheap.
Chapter 2

Background

The second step in the V-model after the requirements are set is the system design phase where information is gathered about the project. Both from requirements but also in general.

This chapter will describe some systems that are important for the understanding of the surroundings of the MOREBAC experiment. It will also discuss earlier projects from NASA that are similar to MOREBAC.

2.1 Cube Satellites

A cube satellite (CubeSat) is a standardized form factor mainly for nanosatellites, satellites which weigh less than 10kg [13]. The satellite is built using a unit frame which can be connected into a larger assembly, usually in a group of 2, 3, or 6 units. A unit has the dimensions 10x10x10 cm. CubeSats are launched either as secondary payloads with other satellites or from the international space station. Due to this the launch cost is lower than if a dedicated rocket would launch the satellite.

The commercial sector has also picked up CubeSats and there are several aerospace companies who specialize on the satellite type. There are pre-made frames, avionics and communication systems available for purchase. Via the major rocket launch companies there is launch slots available which can be booked less than a year before launch.

While buying the component and booking a launch might be simple, requirements from the agency associated with the company responsible for the launch, i.e. NASA or ESA, must be fulfilled. One of the many requirements on CubeSats is that they must have a degenerating orbit causing them to eventually reenter the atmosphere where the satellite will be destroyed. These requirements are to limit space junk in orbit which is a growing problem.

Before a NASA launch the CubeSat must pass several tests to verify requirement compliance. The satellite also experience a "bake out" process where the entire satellite is heated to 70°C. The bakeout is designed to reduce outgassing which can damage optical instruments and reduce efficiency of solar panels. Outgassing is when
trapped molecules in the satellite materials release in gas form when the material is put in vacuum or high temperatures. The process makes CubeSat experiments with instruments and materials that is not able to withstand this temperature over long times difficult for example experiments with living organisms and bacteria.

The high temperature makes it difficult for certain experiments which requires sensitive equipment. This applies to experiments with living organisms and bacteria.

2.2 MIST

MIST is a 3U CubeSat developed by students at KTH. The purpose of the satellite is to supply a platform located in space on which companies and researchers can perform experiments. On MIST there will be 8 different experiments, which is much more than usually found in CubeSats. This makes the space for each experiment limited. In order to fit MOREBAC on this satellite the experiment has to be small and the fluid system has to be in a sub-millimeter/millimeter scale. Hence it is important to study how a system behave in small scale, and what the difference is from a larger scale experiment.

Figure 2.1. Mist satellite without side solar panels. MOREBAC is the dark blue box on the top 1U
2.3 Micro Fluidics

Micro fluidics is the use and control of fluids on a small scale, often sub-millimeter. It is extensively used by researchers in the biological sector and has applications in medicine as well as in chemistry and physics. The research often includes a lab-on-a-chip technology called a fluidics card which is a platform for which experiments can be performed on. The fluidics card usually consists of a set of channels on a acrylic sheet together with different sensors and imaging devices. With today’s technology the process of making fluidics cards is relatively simple and quick and can be made in-house which make them a perfect platform for researchers to work with.

The difference between micro fluidics and regular fluidics is that flow is laminar which means that mixing of fluids can be is different and also difficult. Another difference is that in micro fluidics gravity does not have as much impact as in regular fluids since capillary forces dominate the movement of fluids inside micro fluidic systems.

The fluidics card can be used for chemistry and biology experiment, with small sample volumes. This is beneficial for expensive sample materials for example human blood.

The benefit of using micro fluidic technologies to conduct experiments in space, is the small sample sizes and low space/volume requirements, allowing multiple experiments in self-contained chips.

2.4 Life Support Systems and Bacteria

The long term goal of MOREBAC is to enable transport and use of bacteria for life support systems. A life support system is a system that keep the inhabitants alive by replicating conditions of the natural habitat, ideally in a closed loop ensuring long-term viability.

The purpose of the bacteria is to regenerate life support consumables, for example oxygen renewal and water purification that can be used in a life support system supporting humans. By having these kind of bacteria on long term space missions, such as international space station, the number of resupply missions can be reduced thus presumably lowering costs for space missions in general [6]. It also allows for missions farther away from earth, where resupply missions are not viable. One proposed bioregenerative loop for a Mars base is the MELiSSA loop [8], it includes plants and bacteria for food production with 2 intermediary bacteria steps for degradation of fibers from plant parts which are inedible and bacteria to enable a closed nitrate loop for agriculture.

How the bacteria reacts to space environments over longer timescales is not widely known and to gain knowledge on the subject experiments must be done, in space. Therefore MOREBAC will be investigating one aspect out of many i.e resurrection after a long period.
2.5 NASA’s Biology cube satellites

NASA has flown biological payloads in cubsats on three different occasions. This section covers the scope of these satellites and how the satellites as a whole compares to mist. Further investigation in how the actual experiment was designed and executed will be dealt with in the next chapter.

2.5.1 GeneSat-1

GeneSat-1 was the first autonomous CubeSat from NASA performing gene expression and bacteria growth in outer space. The design and operation is similar to MOREBAC and was therefore investigated. It was launched in 2006.

The fluidics card consisted of 10 culture wells connected in parallel. The fluidics card is made from several layers of acrylic that are laser cut and glued together with pressure sensitive adhesive.

![GeneSat-1 Fluidics Card](image)

Figure 2.2. GeneSat-1 Fluidics Card [10]

Picture 2.2 show the fluidic card from GeneSat-1. The culture wells were filled evenly due to the fiber filter membranes that are placed at the inlet and outlet of each well. These membranes provide fluidic ”impedance matching” at each well because the pressure drop is then across the wells and not the manifold channel itself [19]. The fluidics card is filled with a fluid prior to launch and the only in-space fluidic operation is when replacing the fluid with nutrient [19].

Picture 2.3 shows an exploded view of the nutrient reservoir on the GeneSat-1. The reservoir, which will hold the nutrient pre-experiment, was a medical grade bag with variable volume and pressurized with a pressure plate and two helical springs to provide a pressure of 28 kPa to move the nutrient to the bacteria wells when the experiment is running. Even though it is a fairly primitive solution to generate the pressure it is highly preferable in a CubeSat because it does not include any actuator, which affect the already limited power consumption and also affect
the electromagnetic radiation which could cause problems to the satellites magnetic attitude control. The thermal system consisted of 2 thermal spreaders and 2 thermal heaters that sandwiched the fluidics card [19]. Also 6 temperature sensors were used that were evenly placed along the fluidics card. Before activation of the system the heaters were activated and heated the system from 10 to about 34 which required about 4 W during an hour. After the required temperature was reached the average power to keep the temperature was about 1.8 W [19].

Figure 2.4 shows the temperature (T, black line on top), pressure vessel relative humidity (RH, black curve) and pressure (p, grey curve) of the fluidics card [19].
2.5.2 PharmaSat

PharmaSat was the successor of GeneSat-1, launched 2009, and had a similar design, although some changes were introduced [11]. For example, it studied different microorganisms, the experiment was bigger, and the optical measurement system was redesigned. The Fluidics card consisted of 48 culture wells and 11 solid state reference wells which were never activated by the nutrient[11].

![Cross section of PharmaSat Fluidics card](20)

A cross-section of the fluidics card culture wells can be seen in Picture 2.5. As seen the inlet and outlet to the wells are on opposite sides. This is to ensure that the nutrient is well mixed with the microorganisms for them to grow properly. More of this design choice is further discussed in section 4.3.3.

Another difference to GeneSat-1 is that PharmaSat had pumps to move the fluids. It had 3 different fluids that were mixed with the microorganisms and the pumps made sure precise dilutions, but also increase flow rates for better circulation and mixing. The active heating system consisted of 2 Minco heaters and 2 thermal spreaders that spread the heat evenly across the fluidics card. One of each heater and thermal spreader respectively were placed on either side of the fluidics card. The payloads on the satellite was also well insulated from the external environment but also from the rest of the spacecraft itself. This was to reduce temperature swings from when the sun is shining on the satellite during its 90 minute orbit. This was done by using insulation blankets around the payload and materials with
2.5. NASA’S BIOLOGY CUBE SATELLITES

low thermal conductivity to isolate it from the rest of the spacecraft. Several AD590 temperature sensors were placed around the spacecraft which monitored the temperature and aided the temperature control system. As fall and rise time of the thermal system were known the controller could operate under certain thresholds which enables it to operate at a slow frequency. This helps reduce processor power and also excludes noise from the temperature readings. [5]

2.5.3 O/OREOS

The Organism/Organic Exposure to Orbital Stresses (O/OREOS) was the third of NASA’s biology CubeSats. It was launched in 2010. O/OREOS hosted two biology experiments in the same CubeSat size as the earlier missions. The two experiments, Space Environment Survivability of Live Organisms (SESLO) and Space Environment Viability of Organics (SEVO)[9][15], were both biological experiments. Having two experiments in the same satellite differentiates O/OREOS form the earlier biological CubeSats. The SESLO experiment had a similar scope as MOREBAC, better understanding of survivability of bacteria in space. This experiment was carried out over 6 months, the longest experiment duration of the reviewed systems. The SESLO payload contained 3 modules that were going to activated at different times to study how the microorganisms react to different time periods of radiation. Each module contained its own reservoir of nutrient which made the experiment more space efficient due to the reduce number of plumbing connections [15]. Each reservoir is pressurized with a diaphragm air pump to maintain pressure while the experiment is active. The culture wells were covered with gas permeable membranes which allows exchange of CO₂ and oxygen with the atmosphere around the modules [15]. To keep the fluidic system from freezing an active temperature system was on-board the SESLO experiment. The temperature system had a restricted power resource making the time for heating the experiment a interesting entity to study. A thermal profile was recorded shortly before and during the activation of the first module. The result can be seen in figure 2.6.

The reason why module 2 and 3 reach lower temperatures and are slower is because the heater was located near module 1 and the heat was mainly transferred to the other two modules via conduction [12]. One reason for why there were temperature swings in module 2 and 3 is probably because of the orbit of the satellite which is circa 90 minutes. In the orbit the satellite continuously enters and exits the sunlight resulting in temperature swings. As seen in Figure 2.6 the time required to heat the experiment from 10 to 38 degrees was about 10 000 seconds or about 2.8 hours.
Figure 2.6. Temperature profile for SESLO [12]
Chapter 3

Review of Space Fluid systems

This chapter reviews other, similar, experiments and techniques used within them, to establish a frame of reference for system design. Specifically the fluid actuation systems will be discussed.

Each relevant subsystem from the previous NASA missions will be further investigated and compared.

3.1 Reservoir and Pressurization

The experiment type used requires fluid to supply the bacteria with nutrients/energy, and therefore this fluid has to be contained in the experiment. Because of this the nutrient fluid cannot be stored with the bacteria before the experiment, otherwise the bacteria will consume all nutrient too early in the space flight. When emptying the fluid from the container the weightlessness in free fall comes into play. If the container is rigid, stationary, the fluids surface tension will cause the fluid to stick to the walls creating a cavity in the center of the container. Internal and external pressure can therefore equalize with fluid left in the container. An alternative is to have a container with variable volume. If the volume of the container and fluid is the same, all fluid can be emptied from the container (with external actuation) even in space. The solution lead to the follow up problem on how to move/actuate the fluid. A pump can be used creating a pressure difference which will cause flow. The container can be externally pushed on with a known force creating a specific pressure. This can be set up as a piston cylinder or something that squeezed a bag containing fluid. A third alternative is to have a rotating container where the centripetal motion causes the fluid to always flow to a known area of the container. This solution requires a electric motor, which was deemed in-compliant with MIST requirements due to magnetic fields created either by permanent magnets or coils when the motor is operating.

GeneSat-1 used a spring loaded bag to pressurize the fluid, as can be see in figure 2.3. This system is passive and non electric. The spring loaded design have few moving parts, although they are separate components compared to a pump which is
a single unit. It requires a spring and a piston + cylinder equivalent. In GeneSat’s case a spring loaded plate pushing on a medical bag. The plate is acting as a piston head and can only move translationally in the springs direction. GeneSat-1 did not utilize a waste bag. The bacteria wells only filled once and gas-pressure was relieved through a membrane. Since the entire experiment was in an enclosed container this was permissible and did not cause out-gassing. The drawback of this system is that only a small amount of nutrient can be supplied to the bacteria. Once the fluid is deprived of nutrient it will still remain in the well blocking fluid with higher nutrient content.

PharmaSat also contained the nutrient in medical bags (several bags with different contents) and used two pumps to create a difference in pressure to move and mix the fluids. It also used several waste bags to enable a nutrient flow and ensure isolation of nutrient between wells (see section 3.2).

O/OREOS had a different approach altogether, it did not use medical bags as fluid container. Instead it used a piston + cylinder for each experiment bay (6 in total). The cylinder was integrated directly with the fluidics card into a single unit, and these units were in turn assembled into the final experiment. It did not have a waste compartment. The pressure is generated using small electric motors, one for each cylinder, which generate air pressure from the ambient air to pressurize the piston. When the pressure below the piston increased the piston moved upward forcing the nutrient fluid out and into the fluidic cards.

All three satellites had their experiments in an enclosed container, this meant the experiment had an ambient pressure and temperature.

A drawback from the setup in both PharmaSat and O/OREOS is the use of electric motors to create pressure. The magnetic fields can disturb the other systems on the satellite. In a single purpose satellite this might be somewhat permissible since there at least are no other experiments which can be disturbed. These experiments also use multiple fluid containers (bags respective cylinders), increasing the number of components compare the simpler design of GeneSat. The main pros is the flexibility and added control of nutrient compositions in PharmaSat and no single point of failure in O/OREOS.

### 3.2 Fluidic Routing System

Since MOREBAC would have two separate experiment bays, which would be conducted at different times the fluid had to be directed from the reservoir to the current experiment bay, alternatively have two entirely separate fluid systems. Only the oldest of the previous NASA satellites had a single reservoir with nutrient. This is preferable for MOREBAC since separate systems would include extra components and extra space which is a limited resource in the project. PharmaSat used pumps to move the nutrient from the reservoir to the culture wells in order to increase the circulation and mixing [20]. To direct the nutrient to the correct wells, solenoid valves are used. The use of multiple pumps and multiple valves allowed for mixing.
of the nutrient components and the water. PharmaSat also used multiple waste bags, each controlled by a valve. A separate bag was used for each experiment bay mitigating the risk of back-flow from the waste bag into a different bay. The increase in complexity compared to GeneSat-1 is significant in terms of modes of operation. An overview of the routing system can be seen in figure 3.1.

Both PharmaSat and O/OREOS has the bacteria wells in a single bay mounted in series (in line). Each well causes a drop in pressure (and consume some nutrient) before the fluid flows to the next well. Several wells connected in series therefore causes the pressure drops to cumulatively add up. O/OREOS had its wells connected in series but the different bays where completely separated.

GeneSat-1 had its wells connected in parallel creating junctions that allowed the nutrient to flow in multiple directions simultaneously. This could make the fluid choose one path over the other depending on resistance in the channels, resulting in only one chamber being filled before it exits the fluidics card.

PharmaSat and O/OREOS had no branches or intersections in the fluid routing. If the flow path branches it is not certain how the fluid will flow through the channels. PharmaSat only use directional valves for both merges and branches, therefore only a single path can be active at any given time. Thus it is know exactly which well is being filled or emptied at the moment. This was not the case for GeneSat-1.

3.3 Temperature System

The bacteria need to be kept in a suitable environment even before the resuscitation, hence it is important that the temperature is within the survival range of the
bacteria. All three previous NASA satellites have similar heating systems which consists of the two heaters, one on each side of the fluidics card, and two thermal spreaders to spread the heat evenly across the fluidics card.

All the NASA experiment where conducted withing a sealed compartment, isolating the experiment from the space conditions. This had both thermal and practical benefits for the experiment. Since the compartment was filled with air the surrounding of the fluidics card had a thermal mass, the ambient temperature is more stable compared to a vacuum exposed experiment. Since the satellites were single purpose only the avionic systems (onboard computer OBC) affected the thermal conditions. Heat from processors and similar electronic devices will transfer via the structure of the satellite. The experiment can be isolated from the structure but this reduced the thermal mass of the experiment and was not done for either of the NASA satellites.

If there is no ambient temperature (vacuum) and there is no heating the fluid might freeze. If the medical bags are made to be able to handle frozen liquids, for example used in cryonics, the freezing in not a problem as long as the fluid liquefies before the experiment starts. This adds the issue of knowing if the fluid is in liquid state. The NASA satellites all maintained a internal temperature higher than 0°C, avoiding the problem entirely.
Chapter 4

System Design

The next step in the V-model, after the system design, is the implementation. This is where information from the system design phase is put together to make the system.

Figure 4.1. Exploded CAD render of MOREBAC and its components. Front and side view

Figure 4.1 shows MOREBAC and its components.

The hardware design process was a central part of the work. Component choices, which tries to comply with both NASA and MIST requirements, are discussed here as well as the preliminary design of the module. The components must also fit the biological application to be suitable for the MOREBAC experiment. All decisions was also taken with reference to previous astro-biology experiments, when applicable.
4.1 Requirements

All space machines must comply with rigorous requirements from the local launching agency e.g NASA or ESA. They pose requirements regarding materials, weight and some mechanical limitations to mention a few [3]. Additionally the satellite also has its own, internal, requirements further limiting the choice of components and size.

4.1.1 Mission Outline

MIST will be flying for several years but the MOREBAC experiment module will only be used the first 6 months. Below is a description of the mission outline that describes the order in which each subsystem is activated.

- **Unpowered**
  - During launch the experiment will not have access to any power

- **Non-operational**
  - After launch the satellite will be in detumbling mode and all power is dedicated to the attitude control system of the satellite

- **Experiment One preparation**
  - Fluid actuation
    - Move nutrient to reservoirs

- **Experiment One live**
  - Temperature and Pressure Control
  - Optical bacteria measurements

- **Non-operational**
  - For about 6 months

- **Experiment Two preparation**
  - Fluid actuation
    - Move nutrient to reservoirs

- **Experiment Two live**
  - Temperature and Pressure Control
  - Optical bacteria Measurements

- **Unpowered**
4.2. ARCHITECTURE OF FLUIDICS SYSTEM

4.2 Architecture of Fluidics system

Based on the review of other fluidics systems one architecture was chosen to be built and evaluated. It was decided that a spring pressurized single reservoir would be used to store nutrients. Four valves would be used, two to direct fluid between the experiment bays and two for pressure control in each bay. A common waste bag would be used as the outlet.

![Block diagram of the fluidic dosing system](image)

*Figure 4.2. Block diagram of the fluidic dosing system, the 4 three way valves direct the fluid to the correct bacteria wells and the filters keep the bacteria inside the wells*

Figure 4.2 shows a simplified version of the fluidics card and its components. Figure 4.3 shows the layout of the wells and channels as well as the 4 three way valves that are used.
4.3 Fluidic components

The fluid needed to be distributed to 3 bacteria-wells at a given time, and 3 other wells at a later time. The experiment was to be implemented in a fluidics chip. The outer dimensions of the chip were known, but exact layout only preliminary. This meant several configurations of valves and sensors could be considered. The reservoir which purpose is to hold the fluid until the experiment started was developed as well.

4.3.1 Fluid reservoir

The nutrient will be contained in a 6 ml cryopreservation FEP bag until it is transferred to the wells. The reservoir will be pressurized with four helical springs to a pressure of one atmosphere. This is to make sure that the requirement for the pressure inside the wells are kept at around one atmosphere. In order to generate a pressure of 1 atm the spring will have to generate a force according to the calculations below. With a bag of 6 ml and a area of 19,78 cm², i.e 0,001978 m².

\[ P = \frac{F}{A} \]  

\( P \) is the pressure inside the bag [Pa], \( F \) is the force generated by the springs [N] and \( A \) is the area of the bag [m²]. Given \( P \) as 1 atm or 101325 Pa and the area of 0,001978 m² the force from the springs has to be
4.3. FLUIDIC COMPONENTS

\[ F = PA \] \hspace{1cm} (4.2)

which gives a force of 200 N. This force will be divided onto the four springs that are used, as seen in Figure 4.4.

![Figure 4.4. CAD render of the nutrient bag and its pressure construction](image)

Figure 4.4 shows a CAD model of the pressure system for the nutrient bag. There are four sliding rods, one in each corner of the pressure plate. This is to guide the pressure plate and make sure that it does not shift or tilt when the springs are compressed. The nutrient bag is specified to work in the temperature range between $-200 \, ^\circ C$ to $+200 \, ^\circ C$ and has a maximum volume of 7 ml. With these specifications it should withstand the worst case scenario in terms of temperature which is the cold non-operational case where the temperature is $-27 \, ^\circ C$.

4.3.2 Valves

To direct the fluid to the desired wells at the right time while simultaneously controlling pressure, it was decided to use valves. The choice to use valves depended on several factors. First they needed to be a way to direct the fluid to both the control and later the experiment, an option would have been to have two identical, parallel systems, similar to what O/OREOS[20] used. Having two plus two reservoirs would take more space since the bags needs to be pressurized individually. In Figure 4.3 the valves are shown. They are latching solenoid three way valves. The positive side of using latching valves are that they only need to be powered for a short time in order to change direction, as compared to non latching valves which must have a continuous current running through them in order to change direction of the fluid whilst the experiment is running. The inductance in the valves could be measured with a inductance-meter. This gives an estimation on how much current that is
required per actuation. The data sheets also gives a figure on energy consumption: 5.5 mJ. Power is energy over time meaning that a 5.5 mJ energy consumption over 10 ms period is equal to 550 mW. The current at 5V must therefore be 0.11 ampere, on average.

Most of the material in the valves are approved by the MIST material database [24].

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal</td>
<td>Viton (DuPont, FKM)</td>
<td>Accepted</td>
</tr>
<tr>
<td>Housing</td>
<td>Polybutylene terephthalate</td>
<td>Accepted</td>
</tr>
<tr>
<td>Armature/</td>
<td>Plunger Stainless steel</td>
<td>Accepted</td>
</tr>
<tr>
<td>stop</td>
<td></td>
<td>(if cleaned)</td>
</tr>
<tr>
<td>Spring</td>
<td>Stainless steel</td>
<td>Accepted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(if cleaned)</td>
</tr>
<tr>
<td>Plunger head</td>
<td>Polypythalamide (PPA)</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Table 4.1. Valve material and acceptance status

Table 4.1 shows the material in the valves and if they are accepted by the MIST material database [24].

4.3.3 Fluidics card

The fluidics card consists of three 31 µl culture wells and three reference wells that are going to be tested separately with six months in between in sets of three. The fluidics card is designed so that each well has the same distance to the inlet and outlet ports respectively to have equal pressure in the wells whilst feeding with nutrient and so that they are filled evenly.

![Figure 4.5. Cross section of fluidics card with inlet and outlet to the culture wells](image)

As seen in the cross section of the fluidics card in Figure 4.5 the inlet and outlet are on opposite sides and diagonally across the well to ensure that all nutrient is mixed well with the bacteria. This idea originated from the design of NASA PharmaSat mission were it was stated that it is important that inlets and outlets are diagonally and on opposite sides because the mixing is only through diffusion [20]. The small temperature gradient in the nutrient fluid causes here on earth, where
4.3. FLUIDIC COMPONENTS

Gravity is present, gravity-driven fluid movement due to different temperatures and densities in the fluid and hastens the mixing time. But in micro-gravity this effect does not take place and the mixing has to be carried out when supplying the wells with nutrient [20]. It is important that the bacteria is mixed well with the nutrient in order to have a proper growth. Fluid-permeable membranes are mounted on the inlet and outlet of each well to keep the bacteria confined whilst supplying them with nutrient.
The fairly complex design of the fluidic system required the card to be manufactured from five different layers, seen in Picture 4.6, of optically transparent acrylic that are bonded together with adhesive so that they are structurally linked in order to withstand the internal pressure from the nutrient.

Since the fluidics card is made of acrylic which has been used in space before on the NASA CubeSats mentioned before it should pass the outgassing requirements, though it is not yet verified.

4.4 Electrical hardware

Power consumption was limited to 0.8 W from satellite requirements. This means that all electrical components needed to be chosen with care. Since temperature control will be required for the final module, heating elements will need to be fitted to the fluidics chip. Lowering the heaters power consumption only causes the heating process to take longer time, the total amount of energy is the same (assuming small heat losses) to reach a certain temperature. This further put limitations on the fluidics system and the control system, where there are more options for components.

Since some of the valves used were latching, some additional electrical circuitry was required. To disengage the latch current has to be driven in the reverse direction compete to when engaging. Thus a full H-bridge was required, for each valve that where to be individually controlled.
4.4. ELECTRICAL HARDWARE

All components were controlled by a micro-controller, Arduino Nano 3.X. This was used due to the simple setup, and Simulink support the hardware directly giving us the option to generate the code. It also has a low power consumption. The schematic of the electric system is shown in Appendix D.

The Satellite bus will supply MOREBAC with a 5 V and 14 V power line which was taken into consideration when choosing components such as valves and sensors.

4.4.1 Sensors

A pressure sensor was required to be able to fulfill the system requirements. The closer the sensor could be mounted to the wells the more reliable the data would be. Mounting it in the well was impossible due to the optical sensor used for measuring bacteria needed the wells to be transparent. The sensor was also required to function in vacuum, both as measured pressure and as ambient pressure.

Temperature sensing was also a requirement from the biological system. The bacteria needed to be kept at a certain temperature range, while being resuscitated, measurements are also dependent of the sensing position from the well where the bacteria reside. Thus the temperature and pressure sensors compete for the space close to the wells.

The sensor that was chosen was the MS5837 pressure sensor from TE Connectivity [16]. It was chosen with regards to the requirements of the pressure sensor but also since it also has a temperature sensor built in, which complied with temperature sensor requirements. The sensor can also measure pressure in liquids. Exact material in the sensor could not be found, but they work in vacuum though it is uncertain if they pass the outgassing requirement.

4.4.2 \textit{I}^2\textit{C}

The independent experiments were to be controlled separately and thus two sensors of each type was needed. The chosen sensor communicated via 3.3V \textit{I}^2\textit{C}. But since all sensors of the same type has the same network address when acting as slaves, either two \textit{I}^2\textit{C} buses were required or the bus needed to be multiplexed, i.e. one connected to micro controller and one for each sensor via the multiplexer. Since the decisions to use the Arduino for the thesis had already been made and the Arduino \textit{I}^2\textit{C} works on 5V it was decided to use a multiplexer. It allowed for different voltage levels when relaying \textit{I}^2\textit{C} data while not requiring more space or power that the module would be able to supply. The multiplexer supply power was within what the Arduino could supply from its internal 3.3V voltage regulator.

The protocol for the sensors on the \textit{I}^2\textit{C} bus also contains a 4 bit CRC check-sum to make sure that data is not corrupted when its sent over the bus. This is very important when transferring data in space because of the hostile environment. Bit flips can occur due radiation or SEUs.
4.4.3 H-bridge and valve control

To control the latching three-way valves current had to be routed in both directions in the internal solenoid. This is a common occurrence with inductive loads such as dc-motors and the most common component used to solve this is an h-bridge. When choosing h-bridge size was a major factor. Since 4 valves was to be used all of the had to be independently controlled by an h-bridge. The h-bridge also had to operate at 5V and be able to interface with the Arduino.

The chosen h-bridge was the DRV8833 Dual Motor Driver Carrier from Pololu. Since is was a dual driver in a single chip it could control 2 valves, therefore 2 of the DRV8833 components was needed. While the form factor of the DRV is small a custom h-bridge could be smaller, leaving out unnecessary connections and doubling reverse polarity protection components.

According to the data-sheet of the DRV the component can handle 1.2A continuously. Operating at 5V this correlates to a power of 6W, 750% more than the experiment is allotted from the satellite. But the experiment will never control the valves continuously. To activate a valve current will only run for 10ms.

4.4.4 Power Consumption

The power consumption limit was a hard requirement. During operation the module is not allowed to draw more power than budgeted, since other experiment could be affected. Below is a table with estimated power consumption for each component presented. If the data sheet gives a consumption in ampere (current) I, power consumption P [W] is calculated using Ohms law.

\[ P = U \times I \]  

Where U [V] is 5 volts which is supplied by the satellite.

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
<th>Power Consumption (data sheet) [mW]</th>
<th>Measured Power Consumption [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Nano</td>
<td>1</td>
<td>95</td>
<td>-</td>
</tr>
<tr>
<td>H-bridge</td>
<td>2</td>
<td>unknown</td>
<td>-</td>
</tr>
<tr>
<td>LHD valve</td>
<td>4</td>
<td>550</td>
<td>-</td>
</tr>
<tr>
<td>MS sensor</td>
<td>2</td>
<td>0.00198</td>
<td>-</td>
</tr>
<tr>
<td>( I^2C ) multiplexer</td>
<td>1</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>645</td>
<td></td>
<td><strong>See table 6.1</strong></td>
</tr>
</tbody>
</table>

Table 4.2. Power consumption per component

In the table the heaters are not included, thermal simulations of the entire satellite had to be made to determine how much heat (if any) needed to be supplied to the wells/nutrient fluid. The continuous power consumption can not exceed 0.8 W according to MIST requirements, the fluidic routing components, sensors and
4.4. ELECTRICAL HARDWARE

micro controller will not draw this amount according to the values from table 4.2. The valves though, have a quite high power consumption, but they will only be powered during a short amount of time, 10 ms, and only one at a time so they will not be a problem with regards to the power requirements. But if heating is required a strategy for preheating will be needed, the experiments temperature control will start before the actual experiment.
Chapter 5

Software: Code, Control and Simulation

The experiment were to be controlled from an Arduino Nano. Subsystems were individually implemented and simulated before they were integrated into a master system. Since all models were developed in Simulink integrating them was straight forward. The thermal systems was treated differently. The thermal system was dimensioned theoretically, with estimated parameters.

5.1 Code and Code-Generation

The control software was developed in Matlab/Simulink, while code for specific components were written i C++ and integrated into Simulink.

To read data from the sensor a C++ library was provided by the manufacturer. This library was integrated into a Simulink block, abstracting away the read process. The GCC-AVR compiler included in the Arduino package for Arduino implements parts of the C++ standard, making it possible to generate and compile code from the block to the Arduino.

The H-bridge is controlled directly with digital signals from the Arduino. Simulink has the ability to manipulate the digital pins on the Arduino, thus making H-bridge control simple.

5.2 Valve Logic

In order for the valves to latch the solenoid has to be energized for 10 ms, and since the solenoid must be energized in different directions, depending on the state of the valve, since the valves are latching, each valve state must be known. Thus the state of each valve and an exact timing when changing states is desired. A statechart can be used to model this behaviour.

The logic controlling the latching of the valves was made using stateflow charts. Stateflow is directly integrated in Simulink and can generate code for the microcontroller.
The statechart used for code generation can be shown in figure 5.1. There are two main states: direction 1 and 2, with two substates: latching or latched. The last two blocks controls the hardware pins on the Arduino, the interface between software and hardware. When switching state from one direction to the other, the statechart automatically enters the latching substate which enables the digital pins controlling the corresponding h-bridge for 10 ms. Each valve has its own statechart therefore every valve can independently be controlled.

![Figure 5.1. Logic within statechart for three-way valve](image)

For pure simulations the Arduino interface blocks was removed and the state of the valve in the chart was instead output-ed into the model to enable plotting state over time.

### 5.3 Simulations

With empirical data on the time required to fill up 1 well at operating pressure a simulation model could be done for the pressure valve control.

While the model in figure 5.2 controls the water height of the tank this can be replaced for pressure. In gravity the correlation between water height and pressure is linear, making the switch between pressure and level trivial. But during free-fall the experiment will have to check the pressure difference between the (pre-loaded) reservoir and the inside of the fluidics card. If the pressure has equalized there will be no flow and thus the experiment will assume the tanks are filled. This requires a vacuum in the wells and channels to work as intended. If there is any gas in the system this needs to be let out simultaneously as the nutrient is let in.

The results from the figure 5.2 model can be seen in figure 5.3. From the plot it can be seen when the inlet valve opens and closes depending on the control signal. To ensure that the valves does not repetitively opens and closes when the correct pressure/height is reached, the opening and closing thresholds overlap.
5.3. SIMULATIONS

The model uses a P controller for the pressure regulation. Since the flow is controlled discretely, the valves are either fully open or completely closed, and small errors in pressure is allowed even over long time, a purely proportional controller is enough. The simulated flow were to be validated using calculations from appendix B.2 in combination with flow tests.

![Model for well fill-up process simulation](image-url)

**Figure 5.2.** Model for well fill-up process simulation

![Results from simulation](image-url)

**Figure 5.3.** Results from simulation
5.4 Temperature

To estimate the power needed for the thermal heaters the system has to be modeled. A system can lose temperature from three different types of heat transfer modes.

1. Conduction
2. Radiation
3. Convection

Conduction is the heat transfer of microscopic particles colliding with each other in a body. This type of heat transfer can be from the experiment module to the satellite structure. The radiation losses occur due to that a body emits radiation to its environment. Convection is the loss of temperature due to movement in the surrounding medium. Since the experiment will be in a vacuum there will be no loss of temperature due to convection. Conduction losses can be calculated as

\[ P_{CD} = \frac{KA_c(T_1 - T_2)}{L} \]  

(5.1)

Where the variables are defined as

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Material conductivity</td>
<td>[\frac{W}{mK}]</td>
</tr>
<tr>
<td>A_c</td>
<td>Cross-sectional area</td>
<td>[m^2]]</td>
</tr>
<tr>
<td>T_1</td>
<td>MOREBAC temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>T_2</td>
<td>Satellite Structure temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>L</td>
<td>Length of the conductive path</td>
<td>[m]</td>
</tr>
</tbody>
</table>

Table 5.1. Tables of variables and their definition from equation of conduction losses.

The losses due to radiation is calculated as

\[ P_r = e\sigma A(T_{fR}^4 - T_{aR}^4) \]  

(5.2)

Where the variables are defined as

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Emissivity</td>
<td>[m]</td>
</tr>
<tr>
<td>\sigma</td>
<td>Stefan-Boltzmann constant</td>
<td>[\frac{W}{m^2K^4}]</td>
</tr>
<tr>
<td>A</td>
<td>Exposed area</td>
<td>[m^2]]</td>
</tr>
<tr>
<td>T_{fR}</td>
<td>Final temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>T_{aR}</td>
<td>Ambient temperature</td>
<td>[K]</td>
</tr>
</tbody>
</table>

Table 5.2. Tables of variables and their definition from equation of radiation losses.
These two equations only gives the losses of the system but there is also certain amount of power required to heat the experiment, which can be calculated as

\[ P_H = \frac{mC_p(T_f - T_i)}{t} \]  \hspace{1cm} (5.3)

Where the variables are defined as:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m)</td>
<td>Mass of object to be heated</td>
<td>[kg]</td>
</tr>
<tr>
<td>(C_p)</td>
<td>Specific heat</td>
<td>([J/kgK])</td>
</tr>
<tr>
<td>(T_f)</td>
<td>Final temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>(T_i)</td>
<td>Initial temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>(t)</td>
<td>Time to be heated</td>
<td>[s]</td>
</tr>
</tbody>
</table>

Table 5.3. Tables of variables and their definition from equation of heat capacity

The sum of these three equations gives the total amount of power required to heat the experiment from one temperature to another

\[ P_T = P_{CD} + P_r + P_H \]  \hspace{1cm} (5.4)

The total amount of power that can be given to the heaters can not exceed the power requirement of the experiment, 0.8 W, minus the power from the other components. So in order to have a working thermal system the power to the heaters has to be limited. The part that can be modified in this thesis is the time \(t\) in equation 5.3. The time for the heating can be determined so that the total power matches the power requirements.

By looking at previous work done on the thermal analysis on MIST [1] the worst case scenario for MOREBAC is the cold operational case, were the lowest temperature is -3.7 \(^\circ\)C and needs to be at least 20 \(^\circ\)C. By looking at the worst case scenario for MOREBAC the worst step time for the controller can be calculated.

To calculate the loss or gain in heat from radiation between two surfaces it is important to consider the orientation between the two surfaces. The view factor is a representation of this orientation and is the fraction of radiation emitted by surface \(i\) that is interpreted by surface \(j\) [26]. The view factor can be described as follows

\[ F_{i-j} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi S^2} dA_i dA_j \]  \hspace{1cm} (5.5)

where the variables are described by Figure 5.4

For two parallel surfaces as in the case of MIST and MOREBAC the view factor is in equation 5.6.
CHAPTER 5. SOFTWARE: CODE, CONTROL AND SIMULATION

Figure 5.4. Representation of the view factor [26]

\[ F_{i-j} = \frac{2}{\pi XY} \left( \ln \left( \frac{(1 + X^2)(1 + Y^2)}{1 + X^2 + Y^2} \right) \right)^{1/2} + \frac{X}{1 + Y^2} \tan^{-1} \frac{X}{1 + Y^2} + \frac{Y}{1 + X^2} \tan^{-1} \frac{Y}{1 + X^2} - X \tan^{-1} X - Y \tan^{-1} Y \]  \hspace{1cm} (5.6)

Equation 5.6 is derived from [26]. Where \( X \) and \( Y \) are fractions of the distance between the surfaces and the length and width of them, i.e \( X = a/d \) and \( Y = b/d \).

Figure 5.5. Two opposite, rectangular and same sized surfaces [26]

The variables for equation 5.6 are described in Figure 5.5. The net radiated heat flow between the two surfaces, from surface \( i \) to \( j \), can now be calculated as follows

\[ Q_{ij} = \frac{\sigma(T_i^4 - T_j^4)}{1 - \epsilon_i A_i + \frac{1}{A_i F_{i-j}} + \frac{1 - \epsilon_j}{A_j \epsilon_j}} \]  \hspace{1cm} (5.7)

This is assuming that all radiated heat from the nearby experiment is absorbed by MOREBAC. The experiment above MOREBAC is SEUD and below is a satellite.
5.4. TEMPERATURE

subsystem called IGIS. Using the results from table V and VI in the thermal analysis report, [1], the temperature for each system can be obtained.

Using equation 5.1 the loss from conduction can be calculated where the length of the conduction path is defined as the length of the connection between MOREBAC and the satellite rods/structure. The material conductivity is defined by table 4.20 in a previous thermal analysis of MIST, [4]. $T_2$ is the satellite structure temperature.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.1</td>
<td>W/mK</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$3.18 \times 10^{-5}$</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$T_1$</td>
<td>269.45</td>
<td>K</td>
</tr>
<tr>
<td>$T_2$</td>
<td>223.45</td>
<td>K</td>
</tr>
<tr>
<td>L</td>
<td>0.028</td>
<td>m</td>
</tr>
<tr>
<td>e</td>
<td>0.95</td>
<td>m</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$5.670373 \times 10^{-8}$</td>
<td>$W/m^2K^4$</td>
</tr>
<tr>
<td>$A_{SEUD}$</td>
<td>$0.01$</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$A_{IGIS}$</td>
<td>$0.01$</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$T_{fR}$</td>
<td>269.45</td>
<td>K</td>
</tr>
<tr>
<td>$T_{ar-SEUD}$</td>
<td>266.25</td>
<td>K</td>
</tr>
<tr>
<td>$T_{ar-IGIS}$</td>
<td>251.95</td>
<td>K</td>
</tr>
<tr>
<td>$m_F$</td>
<td>0.088  (Fludics card)</td>
<td>kg</td>
</tr>
<tr>
<td>$m_W$</td>
<td>0.006  (Water)</td>
<td>kg</td>
</tr>
<tr>
<td>$C_{pF}$</td>
<td>1465 (Acrylic)</td>
<td>J/kgK</td>
</tr>
<tr>
<td>$C_{pW}$</td>
<td>4185.5 (Water)</td>
<td>J/kgK</td>
</tr>
<tr>
<td>$T_f$</td>
<td>293</td>
<td>K</td>
</tr>
<tr>
<td>$T_i$</td>
<td>269.45</td>
<td>K</td>
</tr>
<tr>
<td>t</td>
<td>See section 7.1.4</td>
<td>s</td>
</tr>
</tbody>
</table>

Table 5.4. Power Consumption Variables

With the values in table 5.4 the sum of the heat losses, i.e $P_{CD} + \dot{Q}_{ij}$, adds up to about 0.031 W. The power available for the heaters is about 0.65 if the power from the other components are deducted from the total available power.

A supplier of heaters is Minco which the NASA satellites used on their biological experiments in space mentioned before. These heaters are NASA approved for outgassing and using in vacuum. In the Minco guide, [14], it is suggested that the resistance is calculated using the power requirements together with the supply voltage to the heater using the following formula

$$ R = \frac{V^2}{P} $$

(5.8)

where $V$ is the voltage [V] and $P$ is the power [W], when choosing heaters. Using a voltage of 5 V and a power of 0.65 W the resistance is 38.46 Ω. The closest heater
to this value is Polyimide $\text{Thermofoil}^{TM}$ Heaters: HK6904, [18], with a resistance of 38.94 $\Omega$. This will give an actual power of 0.64 $W$, which is still feasible and will not affect the rise time noticeably.
Chapter 6

Tests and Results

To evaluate the fluid actuation system several tests were conducted. The goal of the test were to evaluate if the system design was suitable for space, conforming with requirements and functioning as expected. The right vertical axes of the V-model includes testing of each subsystem and later integrate them together and make a test of all components together. Each component in this project had been tested separately and later some of the components was tested together.

6.1 Flow tests

The flow tests were designed to test how the fluid flow in the fluidics card and how well the directional functionality worked.

A test was performed to estimate the flow rate of the tubes and channels. Using a pressure controller the inlet pressure was set to 1 \text{Atm}.

With a input pressure at 0.5 \text{Atm} and output pressure at less than 0.5 \text{Atm}, the filling process of one well was measured. Since the entire structure was not sealed enough to maintain 0 \text{Atm} on the output, the input pressure was raised so the pressure difference would be 1 \text{Atm}. Since the pressure controllers could supply air faster that the leaks the pressure difference could remain constant even with leaks. While the filling process was continued after the first well was filled the other well did not fill up since the fluid continued to flow to the output.

A test with vacuum was designed but could never be completed. The goal was to remove all air from the wells and channels. Then close the output and supply fluid. In theory all wells should then be able to completely fill and the time this takes can be measured. This test would be the closest to the actual conditions in space, disregarding gravity which has negligible effects.

6.1.1 Pressure

A pressure controller was used to measure the pressure needed for moving the nutrient in the channels to the wells. A pressure of 7 \text{kPa} was needed. Although,
one well on the fluidics card was filled before the others.

### 6.1.2 Pressure control test

Using a pressure controller on the inlet of the fluidics card the pressure inside the channels and wells were controlled with the pressure sensor and valves at the outlet. With the use of the pressure sensor the control loop can be closed while the pressure controller can be used as control to ensure plausible readings from the sensor.

### 6.1.3 Power Consumption

To ensure compliance with the power limitation requirements the current draw with the full system was measured. All components was also measured independently. From the current the power in watts could be calculated as

\[ P = UI \]  

(6.1)

where \( P \) is the power [W], \( U \) is the voltage [V] and \( I \) is the current [A]. The power drawn from the sensors, multiplexer and the H-bridges is so small that they are negligible in this context. So the only components worth examine are the Arduino and the valves. Through the measurements it was stated that the power of the Arduino is circa 150 mW. Since the valves only are activated a fraction of a second most ampere-meters are too slow to measure the exact current. But since the coil in a valve is current inert only a small amount of current can flow during the small activation time.

If a component did not give any change in the ampere meter measured value with \( 10^{-3} \)A precision, the power consumption was deemed negligible. Estimated power consumption and measured power consumption for selected components can be seen in table 4.2

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
<th>Power Consumption (data sheet) [mW]</th>
<th>Measured Power Consumption [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Nano</td>
<td>1</td>
<td>95</td>
<td>150</td>
</tr>
<tr>
<td>H-Bridge</td>
<td>2</td>
<td>unknown</td>
<td>Negligible</td>
</tr>
<tr>
<td>LHD valve</td>
<td>4</td>
<td>550</td>
<td>490</td>
</tr>
<tr>
<td>MS sensor</td>
<td>2</td>
<td>0.00198</td>
<td>Negligible</td>
</tr>
<tr>
<td>( I^2C ) multiplexer</td>
<td>1</td>
<td>0.1</td>
<td>Negligible</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>645</strong></td>
<td><strong>640</strong></td>
</tr>
</tbody>
</table>

*Table 6.1. Component Power Consumption*

### 6.1.4 Component Masses

The mass of the system must be measured to ensure that the mass budget requirement is met.
6.1. FLOW TESTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
<th>Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Nano</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>H-Bridge</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>LHD valve</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MS sensor</td>
<td>2</td>
<td>0.014</td>
</tr>
<tr>
<td>$I^2C$ multiplexer</td>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>Fluidics card</td>
<td>1</td>
<td>88</td>
</tr>
<tr>
<td>Nutrient</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Nutrient pressure system</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>&lt;125</strong></td>
</tr>
</tbody>
</table>

*Table 6.2. Component Individual Masses*

Table 6.2 gives the weight of each component separately. The weights was measured with a scale and the total mass for all components including the case was estimated to about 225± 5 g. With a volume of 0.231384 dm$^3$ the density is about 972 g/dm$^3$. 
Chapter 7

Conclusions

7.1 Discussion

7.1.1 Fluidics card

When filling the fluidics card with nutrient it was noted that only one of the wells filled up and water got to the outlet before filling up the other two culture wells. The reason for this could be that the resistance in the two channels is higher because of trapped air in the wells causing an internal pressure from the well keeping the inlet nutrient from reaching all wells and go to the outlet instead. Another reason could be because of different friction in the non-common channels causing the liquid to move through the channel with the least friction.

A possible solution could be to remove the air in all channels and wells before launching the satellite and filling the card with nutrient. This vacuum will remove the resistance from the air in the wells and possibly letting the nutrient reach each well before going to the outlet.

Another solution to this problem could be to have the culture wells connected in series instead of them being parallel to one another. This will let the liquid get to each well before exiting the outlet. But this design could cause problem with the needed pressure to fills the wells. Since each well needs a filter to be placed on the inlet and outlet of each well will cause extra resistance for the liquid to move because of the wells being connected in series the resistance gets higher for each well the liquid passes.

7.1.2 Pressure tests

Since the pressure tests and pressure control test never were able to be done in desirable conditions, the results from those test are somewhat inconclusive. But the tests showed that even with lower pressure than desired the valves work as intended and fluid flows at an acceptable rate. The main problem during the test was the residual air in the channels, not the leakage, which is a problem for the sealed fluidics card as well. The air gets trapped in one or two wells while the
majority of fluid flow through the other. If there was vacuum in the well before the fluid enters the fluid would fill all wells, given enough time.

### 7.1.3 Mass

The estimated mass of the system was 225 g but this is with the components for this project excluding the LEDs and sensors used for growth detection. The estimation is probably an overestimate because of the several PCBs that are used in this project. With only one PCB the mass would be lower but could be about the correct mass for the whole system including the growth detection components. The density of all the components combined is just below the mass budget.

### 7.1.4 Temperature Controller

With the result from calculating the heat losses of the fluidics card the rise time of the controller can be calculated.

![Figure 7.1. Power to heaters plotted against time required to heat the experiment during cold case operational](image)

Picture 7.1 shows how much time is needed to heat the experiment for a specific power during the operational cold case, i.e. the worst case. As seen in the figure the time is quite substantial and it can be noted that the limited power requirement of 0.8 W affect the temperature controller. But the values used is for a worst case scenario and when previous thermal states are not taken into consideration. The
cold operational case is when the satellite is furthest away from the sun, that is during the summer solstice. But if previous states are taken into consideration when the satellite was warmer, this heat could be stored and used during the worst case scenario so that the power required to heat the experiment is much lower. A way to store the heat would be to insulate the experiment with so called Multi-layer insulation. This reduce the heat losses due to radiation and temperature swings during the orbit. Previous thermal analysis of the experiment even shows that MOREBAC itself produce too much heat from its lower PCB. Due to this it was decided that thermal heaters are not going to be used in the experiment until a more thorough investigation of this has been made. One solution would instead be to mount rods with high thermal conductivity on the payload to lead the excessive heat from the experiment to the satellite structure.

7.2 Conclusions

The design of the space fluidics system is an viable option for the experiment. Not having an ambient pressure can be overcome and the experiment can, barely, comply with power consumption requirements. But the parallel design of well placement is an unnecessary risk, gas bubbles or uneven flow resistance might cause some wells to not function at all. Therefore the risk of having the wells in parallel overshadows the benefits of independence and potential higher average pressure. If the system were to be redesigned it would have the wells in series. Nevertheless similar setups have been successfully used previously.

All selected components have worked as intended with the only caveat that some will not fit in the small experiment compartment. At least not with the current iteration of fluidics card.

Since the fluidics card was designed with a margin for future membranes the resulting design became 9 mm thick. Once the exact membranes, and exact well configuration, have been decided a optimized design of the fluidics card can be done, hopefully reducing the thickness of the card. One of the last steps in the V-model is to ensure that system meets the requirements set in the beginning of the project. To reference back to the requirements of the system the following can be concluded.

- The system meets the power requirements as seen in table 6.1 where the total power, $0.64 \, W$, is lower than the available, $0.8 \, W$.
- The fluidics card consists of 6 culture wells
- The density of the system is about $972 \, g/dm^3$ which is less than the mass budget.
- As mentioned before the requirements regarding the module dimensions can be met if certain changes are made to the system.
- The temperature is still unsure
The system should be able to keep a pressure of 1 bar from the nutrient pressure system, although not yet verified.

Some of the components are verified to meet outgassing requirements.

EMC is not yet verified because of uncertain requirement limits. Although the EMC was considered when choosing components and designing the sub-systems.

The current electronics can be interfaced with the electronics on MIST. All components use 5V or otherwise a voltage regulator is used. For example the built in voltage regulator on the Arduino.

The fluidics card consist of two separate channels with three wells respectively.

7.3 Futurework

Thermal analysis is the main task that should be done to improve the chance of a successful mission. If the nutrient freezes and the thermal heaters can not provide enough energy the mission is an instant failure. How and if the experiment should be insulated, from the other components and the sun should be known before the hardware/software for thermal control is decided upon.

1. Since the PCB consists of, at the moment, other PCBs such as the Arduino and the H-bridge etc. it takes a lot of space height wise. This makes it impossible to fit everything inside the specified dimensions for the MOREBAC experiment. But by redesigning the PCB (and /or fluidics card) it will be possible to fit everything in the experiment module. One way to do the redesign would be to have all the components from each of the other PCBs mounted on one PCB instead, which will save space, both by not having connectors for unused pins and possibly reduce over all volume.

2. A more substantial thermal analysis to make a more reliable model for the thermal controller.

3. Full system test in vacuum, especially if the fluidics card remains sealed and how and if the sensors are affected by the vaccum.

4. The experiment needs to have a protection for the battery bus to protect the battery from shorts from MOREBAC.

5. Tests to verify outgassing requirements
Bibliography


[10] Christopher Kitts et al. “Flight Results from the GeneSat-1 Biological Microsatellite Mission”. In: ().


[12] Christopher Kitts et al. “SSC11-III-3 Initial On-Orbit Engineering Results from the O/OREOS Nanosatellite”. In: (). URL: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=11197B%5C&%7Dcontext=smallsat.


Appendix A

MOREBAC Requirements

1. Physical Experiment bounding box
2. Power requirements (0.8W)
3. Target no of growth chambers: 6
4. Mass limitation - < 1 kg/dm³
5. Module dimensions - ca 2x2x3 inches
6. Chamber dimensions - 10 mm diameter, 2 mm height
7. Temperature.
   • 4-30 °C at all time
   • 20-30 °C during experiment
8. Pressure: Between 1-2 bar in chambers at all time
9. Materials must conform to NASA standards
   • Accessed via MIST Material table [23] [24] and
   • NASA STD 6016
10. EMC - parts must have low electromagnetic emissions to not disturb other systems From NASA standard GSFC-STD-7000A
11. Interfacing - the electronics should interface with previously developed control electronics and make use of one of the micro controllers previously tested.
   • 5V is accessible
   • 14 V from Battery is accessible (Not steady)
12. Two separate channels for each 3 of chambers on fluidics card (FC)
Appendix B

Various calculations

B.1 Ambient pressure

Is ambient pressure 0 Pa a reasonable assumption in the mist satellite use case? Satellite will fly at roughly 470km. Using the NRLMSISE-00 [17] model and the ideal gas law gives an estimation of the pressure. The pressure $P$ is sought, where $\rho$ is the density of the air, $R_{\text{specific}}$ is the specific gas constant and $T$ the temperature.

$$P = \rho \times R_{\text{specific}} \times T \quad (B.1)$$

With $\rho = 1.25 \times 10^{-15}[g/cm^3]$, $R_{\text{specific}} = 287[J/(kg \times K)]$ and $T = 960[K]$ the pressure is estimated to, $P = 3.4 \times 10^{-10}[Pa]$. This being $10^{-13}\%$ of the internal pressure (magnitude wise) it was decided that ambient pressure could be neglected.
APPENDIX B. VARIOUS CALCULATIONS

B.2 Channel Velocity

This section describes the calculations needed for calculating the time for filling the channels and wells on the fluidics card. Picture B.1 will be used to visually demonstrate one channel of the fluidics card, including inlet/outlet channel but also a well. This setup is before the channels and wells are filled and it is just before a experiment has started. Therefore the pressure in the well and in the outlet is zero and there is 1 \text{ atm} of pressure at the inlet from the nutrient reservoir.

\[
\begin{align*}
P_1 &= 1 \text{ atm} \\
h &= 0.5 \\
w &= 1 \\
D &= 10 \\
P_2 &= 0 \text{ atm} \\
P_3 &= 0 \text{ atm}
\end{align*}
\]

Figure B.1. Fluidic system

Using Bernoulli’s equation:

\[
P + \rho gh + \frac{\rho v^2}{2} = \text{Constant} \quad (B.2)
\]

where \( P \) is the pressure at a chosen point, \( \rho \) is the density of the fluid, \( g \) is the acceleration due to gravity, \( h \) is the elevation from a reference point and \( v \) is the fluid flow speed at a point in the streamline. As seen in the equation above one of the summands include the acceleration due to gravity. Since this experiment will be performed in free fall this summand can be neglected, thus resulting in the following equation:

\[
P + \frac{\rho v^2}{2} = \text{Constant} \quad (B.3)
\]

Since Bernoulli equation is constant for all channels and wells it will give the following equation system:

\[
P_1 + \frac{\rho v_1^2}{2} = P_2 + \frac{\rho v_2^2}{2} = P_3 + \frac{\rho v_3^2}{2} \quad (B.4)
\]

The pressure at the inlet is 1 \text{ atm} at the beginning of the experiment and the outlet and the wells have a pressure of 0 \text{ Pa}. By removing \( P_2 \) and \( P_3 \) and rearranging the following equation will be obtained:
B.2. CHANNEL VELOCITY

\[ \frac{2P_1}{\rho} + \nu_1^2 = \nu_2^2 = \nu_3^2 \] \hspace{1cm} (B.5)

Assuming the nutrient fluid is incompressible the volumetric flow is constant across all channels and wells, resulting in the following equations:

\[ A_1V_1 = A_2V_2 = A_3V_3 \] \hspace{1cm} (B.6)

Where A is the cross sectional area of the channels/wells. As \( A_1 \) and \( A_3 \) are the same \( V_1 \) and \( V_3 \) will also be the same.

The two equations B.5 and B.6 gives the equation system to be solved. In order to solve this equation system one of the fluid flow speed has to be known. This was done by performing an experiment with a pressure controller and measuring the volumetric flow.
Appendix C

Components

Figure C.1 shows the components used in this project and their prices.
Figure C.1. List of components that are bought for MOREBAC

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Unit</th>
<th>Price</th>
<th>Amount</th>
<th>Size (m)</th>
<th>Other Details</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

58
Appendix D

Electric Schematic

Figure D.1. Electric Schematic