STA 1- SPACE TECHNOLOGIES ON ALPINISM: PHASE ONE

Study and development of a high altitude mountaineering Mitt

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Alexandre João Nunes Flórido
Coimbra, 4 September 2011
“Nas faldas do Himalaia, o Himalaia é só as faldas do Himalaia. É na distância ou na memória ou na imaginação que o Himalaia é da sua altura, ou talvez um pouco mais alto.”

Fernando Pessoa
ABSTRACT

Alpinism is a sport of high risk, with few practitioners. It is a demanding and dangerous sport due to the extreme environmental conditions. The health consequences caused by the very low temperatures and high-altitudes happen and are inevitable. However, with appropriate equipment those sequels may take longer to settle in a severe way and with permanent damages.

The present work, named STA 1 project, is the first phase of the bigger project “SPACE TECHNOLOGIES ON ALPINISM”, and intends to develop a mitt, using the newest technologies available and an intelligent system of temperature control, that will help the alpinist perform without suffering severe consequences of long-term exposure to the cold and high-altitude, like frostbite in the hands, causing amputation of the fingers, and even compromise the athlete survival.

Keywords:
Alpinism, frostbite, hypoxia, dehydration, hypothermia, heat transfer, mitt, alpinist, High Mountain, low temperature, high-altitude, thermal comfort, insulation materials, dew point, relative humidity, metabolism.
**RESUMO**

O alpinismo de alta altitude é um desporto de alto risco, sendo poucos os praticantes que o realizam. É um desporto exigente e perigoso devido às condições ambientais extremas a que o alpinista se submete. As sequelas causadas pelo extremo frio e pelo ar rarefeito acontecem e são inevitáveis, no entanto com um equipamento apropriado podem demorar mais tempo a instalar-se de uma forma severa e com danos permanentes.

O presente trabalho, designado por projecto STA 1, é a primeira fase do projecto maior “SPACE TECHNOLOGIES ON ALPINISM”, e tem como objectivo o desenvolvimento de uma luva, utilizando as tecnologias mais recentes, bem como um sistema inteligente de controlo de temperatura, que ajuda o alpinista a realizar a sua expedição sem que sofra sequelas graves causadas pela longa exposição ao do frio e à alta altitude, como o enregelamento das mãos, que pode levar à amputação dos dedos ou ao comprometimento da sobrevivência do atleta.

**Palavras-chave:**

Alpinismo, enregelamento, desidratação, hipotermia, transferência de calor, luva sem dedos, alpinista, Alta Montanha, baixa temperaturas, alta altitude, conforto térmico, materiais de isolamento, ponto de orvalho, humidade relativa, metabolismo.
ACKNOWLEDGEMENTS

The work developed provided me a great chance to increase my knowledge in this area and to grow as a professional. For that, it is a pleasure to me to express my gratitude to everyone who made this work possible.

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I must thank Dr. Francisco Fraga for all the help and availability to solve any problem and to Prof. Dr. Rui Marques for all the discussion and help regarding the preparation of this document.

I cannot end without thanking the professional Alpinist João Garcia for the inputs given to this work, which became essential to all the decisions made for this Project.

To my family, that always supported me in all my decisions, I dedicate this work.
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1. INTRODUCTION

1.1. MOTIVATION

Alpinism is a very demanding activity because it is practiced on extreme environmental conditions, and is not unusual to hear about people dying during expeditions. In fact, as an example, between the year 2000 and 2010, the K2 Mountain has taken the life of over 20% of its climbers. The cold and the altitude are the main enemies of the alpinist. To overcome these two obstacles, certain conditions are necessary to ensure the survival of the climber. These conditions are related with nutrition, hydration, clothing, equipment, experience, etc. When everything goes as expected, the climber ascends, accomplishes his goal and then descends without major sequels, but it is not always like that. After reaching the top successfully, many people suffer the consequences of their audacity, during descend.

The most common sequels that people suffer are the lost of weight, dehydration and the lost of the body extremities (ears, nose, fingers and toes). The consequences due to coldness are often a sign of not wearing adequate clothing. A garment that does not allow the use of the heat produced by the human body will make the body activate physiological mechanisms to protect itself from extreme environmental conditions, but due to the extreme conditions, the body cannot maintain the balance. In order to cope with its limitation, the body starts to take survival measures, like blocking the blood supply to the extremities.

In the last 20 years, there was not significant development in sports clothing, related to Alpinism. With today's technology, it shall be possible to optimize the clothing in alpinism in a way that maximizes the comfort of the athlete, significantly reducing some of the consequences caused by the cold.
1.2. PROJECT OBJECTIVES

The objectives for the STA 1 are:

1. Design a mitt that prevents the alpinist hands temperature of reaching dangerous values, which results in permanent damages;

2. Guarantee the maintenance of a proper hand temperature with the help of an electronic control heating system, during an expedition in high-mountain above 7000m with temperatures of -30ºC and a wind of 10m/s;

3. Develop an adequate solution to Alpinism needs, making more efficient than the solutions available in today’s market;

1.3. DISSERTATION OVERVIEW

The present document is divided into 7 chapters. This section makes a brief description of each one.

**INTRODUCTION** – a brief introduction to the project is presented, as well as the motivation, the project objectives and an overview of the team involved in this project.

**THEORECTICAL BACKGROUND** – provides the information related to the physiological behaviour of the human body at low temperatures and explains some of its consequences. Includes basic concepts about some meteorological parameters, and theoretical concepts regarding heat transfer.

**SYSTEM OVERVIEW** – in this chapter, it is included a global presentation of the solution found to accomplish the project objectives.

**MATERIALS** – presents the materials applied in today’s sports (hi-tech fabrics) their characteristics as well as a technical discussion that leads to a proposed solution to solve the problem in question and finally the materials chosen for the project. It also presents the calculation of heat transfer.
ELECTRONIC SYSTEM DEVELOPMENT – in this chapter are explained all the choices made to accomplish every part of the electronic thermal control of the mitt.

THERMAL TEST VALIDATION – here are analyzed the results of the tests that were performed with the mitt prototype.

CONCLUSIONS – the final impressions, concerning the mitt prototype, are presented.

FUTURE WORK – it contains, after the obtained results, the issues that could need improvement and features for future prototypes.

1.4. PROJECT TEAM

The project STA1, was developed at Active Space Technologies, a company of aerospace technology that is established in IPN (Instituto Pedro Nunes). The TABLE 1 shows an overview of all the people involved in the project.

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Abel Mendes</td>
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<td>Jessica Hernández</td>
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<td>Nuno Rocha</td>
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<td>Jorge Pinho</td>
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</tr>
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<td>André Tenreiro</td>
<td>IT support</td>
</tr>
<tr>
<td>Joaquim Varandas</td>
<td>Electronics Engineer</td>
</tr>
</tbody>
</table>

**TABLE 1 - Project Team**
2. THEORETICAL BACKGROUND

2.1 THE HUMAN BODY IN HIGH-MOUNTAIN

Over the past few years there was an increased interest of people towards mountain sports. Some of these, including mountaineering and skiing, are practices in a non natural environment for human beings. Man is the only living being native to the regions at sea level that exposes himself, deliberately and for reasons other than those of survival, to the rigors of very low temperatures and hypoxic environments present in mountains of high altitude. This kind of behaviour puts the body to the test and triggers physiological reactions that guarantee its survival. But sometimes those reactions are extreme causing organic unbalances (dehydration, hypothermia and hypoxia) and mutilations (frostbite). For these reasons, great emphasis has been given to the study of human physiological response to high altitude environments (1; 2).

In this chapter it will be discussed some consequences of the very low temperatures and high altitudes in the human body, as well as a brief explanation of the metabolism process. The understanding of these subjects was important because it helped to decide the best strategy to fulfil the project goals.

2.1.1. Pathologies related to Alpinism

2.1.1.1. Dehydration

Dehydration is one of the main health hazards associated with cold environments. Studies made in the U.S.A. showed an increased risk for dehydration in cold environments, a condition more commonly associated with hot weather (3).

Dehydration is defined as the excessive loss of body fluid. When it occurs, there is an unbalance between the amount of water eliminated and the amount of water ingested (4; 5).

Water is vital for our body’s normal function. In normal conditions, our body maintains a constant total volume of water, being "the total amount of water in an average weight
man (70 kg) approximately 40 L, representing 57% of his total body weight." Normally the amount ingested is the same as the eliminated. The total volume of water that enters in the body varies between 1500 – 3000 ml, a day. Most of it (90%) comes from the liquids we ingest and 10% comes from the food and from the cellular metabolism (5).

The excessive loss of body water is a dangerous situation. In normal condition our body looses water in three different ways. The major amount is trough urine, The evaporation via the airways and by the skin (sweat) represents, approximately, 35% of the lost water. The remaining 4% represent the lost of water by faeces (5).

The amount of water lost by sweat and by the respiratory system depends on the environmental temperature, pressure, humidity, body temperature and the volume of air exhaled. All this regulation is maintained by the hypothalamus. The anterior hypothalamus detects small temperature increases; the posterior hypothalamus detects small temperature decreases. When the body core temperature rises, the body releases water in the form of vapour (sweat), quickly decreasing the temperature. When the body core temperature decreases, the body reacts constricting the vessels and shivering. The mechanism seems very simple and logic, but at low temperatures and high-altitude the human body is in an extreme situation and struggles to keep the balance. At those extreme conditions the environment changes so quickly that the human body doesn't have the capacity to compensate at the same pace and for that fact the heat and fluid losses are higher than they should be (4; 5).

As we mentioned earlier, the higher loss of water is through urine (61%). That percentage was determined in “normal” environmental conditions (23 °C and 1 atm), but at low temperatures the loss of water by urine is even higher, because the body needs to increase the body core temperature, and when it contracts the vessels (vasoconstriction) of the body extremities, the blood circulatory volume decreases and the arterial blood pressure increases, so the body releases the arterial blood pressure producing more urine. That mechanism combined with the low atmospheric pressure in high-altitude (osmosis mechanism) provides an inevitable dehydration of the body (1; 5).

In a primary stage of dehydration, the body activates the sensation of thirst to increase water intake and decreases the urine output to try to conserve water loss. The urine becomes more concentrated and more yellow in colour. As the water loss increases, more symptoms appear. Below are presented symptoms of a more severe dehydration (3).
- Dry mouth;
- The eyes stop producing tears;
- Sweating may stop;
- Muscle cramps;
- Nausea and vomiting;
- Heart palpitations (Tachycardia);
- Light-headedness (especially when standing);
- Weakness;
- Decreased urine output

The body tries to maintain the cardiac output (amount of blood pumped by the heart to the body). If the amount of fluid in the intravascular space is decreased, the body tries to compensate that deficit, raising the heart rate (tachycardia) and constricting the vessels, in order to maintain the blood pressure and the right oxygenation of the vital organs. This mechanism begins to fail as the level of dehydration becomes more severe. When there is a high level of dehydration, mental confusion and body weakness appear, because the brain and the other vital organs don’t have enough blood supply. A stroke may happen too, because the blood is too thick and may form clots. If not treated, dehydration becomes a life threat situation, leading to a coma or, in the worst case scenario, to death (through organ failure) (3).

2.1.1.2. Hypothermia

Hypothermia is one of the problems that the human body faces when dealing with cold environments. It’s important to know what it is, how it happens, what the symptoms are and how to prevent it.

The human body maintains a relatively stable temperature; the heat production is balanced by heat loss. Hypothermia occurs when the normal core temperature of the body, 37°C (98.6°F), decreases for less than 35°C (95°F). When a person is exposed to a cold environment (wind, snow, rain or water immersion) the body’s heat production decreases and hypothermia occurs (hypo=less + thermia=temperature). Anyone exposed to cold temperatures, whether for work or recreation, may be at risk of becoming too cold (1; 4).
Hypothermia is a physiological reaction, consequence of a long-term exposure to cold environments. Normal body temperature it’s a delicate balance between heat production and heat loss. Its right balance is essential because there are specific chemical reactions, which allow the survival of the human body, that only occur in specific temperatures ranges. The brain, more specifically the hypothalamus, is the organ that coordinates all the mechanisms that maintain vital temperature, and if these mechanisms are overwhelmed, heat loss happens faster than heat production, resulting in hypothermia (2; 4).

The signs and symptoms change depending on the degree of hypothermia and can be described in four stages of severity (mild, moderate, severe and profound) (6). The distinctions among mild, moderate, severe and profound hypothermia are not often clear, but the constant sequence of events occur as the body core temperatures continues to decline.

- **Mild hypothermia**: 35ºC to 32ºC (95ºF to 89.6ºF). The symptoms are mechanisms to preserve and produce heat: shivering, hypertension, tachycardia, tachypnea and vasoconstriction. In this stage, some people may present already some confusion, apathy, lethargy, cold diuresis and hypoglycaemia (2; 6).

- **Moderate hypothermia**: 32ºC to 28ºC (89.6ºF to 82.4ºF). At this degree of severity the shivering becomes more violent and eventually stops, because it spends too much energy. The heart rate decreases (bradycardia) and becomes irregular (arrhythmia). Muscle discoordination becomes evident and the movements are very slow and laboured. The mental confusion, or delirium, appears due to the vasoconstriction in the brain, but the individual may seem alert. In this degree of hypothermia the body also initiates the vasoconstriction of the extremities, because the body focuses its remaining resources on keeping the vital organs warm. The victim becomes pale and the lips, ears, fingers and toes may become blue (cyanosis). There is a high risk of frostbite (2; 6).

- **Severe hypothermia**: below 28ºC (82.4ºF) the cellular metabolic process shut down, “…walking becomes almost impossible, and the victim exhibits incoherent/irrational behaviour, including terminal burrowing behaviour or even a stupor (…) Pulse and respiration rates decrease significantly, but fast heart rates (ventricular tachycardia and ventricular fibrillation) can occur.” (2; 6)
- **Profound hypothermia**: below 20ºC (68ºF). Major organs fail, brain activity stops and clinical death occurs \(^{2; 6}\).

Hypothermia is a serious and deathly consequence of the extreme cold and must be prevented. A good nutrition state and appropriate clothes are vital \(^{2}\).

2.1.1.3. Hypobaric Hypoxia

Hypoxia is a state of low presence of oxygen in the body tissues, whose occurrence is attributed to several factors. It may be caused by internal factors like an anomaly in the mechanism of transport of oxygen, a physical obstruction of the blood flow in the vascular system and anaemia or by external factors like low concentration of oxygen in the air environment (high-altitudes). Hypobaric is related to "conditions of low air pressure and low oxygen content, such as atmospheric conditions at high-altitudes, or in special chambers used to establish low-pressure conditions." \(^{7; 8}\)

As the altitude increases, there is a decrease in the barometric pressure as well as in the quantity of the oxygen in the air (GRAPHIC 1). This phenomenon causes changes in the quantity of oxygen present in the arterial blood and, consequently, the "amount" of oxygen delivered to tissues \(^{9}\).

![GRAPHIC 1 – Atmospheric pressure versus Altitude](image-url)
Evangelista Torricelli, disciple of Galileo, was the first person to assume that air had weight. As he stated in 1644, ‘we live submerged in the bottom of an ocean of air that, through unquestionable experiments, have weight on us.’ So, taking as reference the barometric pressure at sea level (760 mmHg), as we climbed in altitude the pressure exerted by this layer of air (barometric pressure) decreases. At an altitude of 5800 meters, the barometric pressure decreases to about half (379 mmHg) of the value reported at sea level and on the summit of Everest (8850 m) assumes values of about one-third (253 mmHg) of the sea level pressure. The quantity of breathable oxygen is directly proportional to the barometric pressure; the higher we climb the less oxygen is available (GRAPHIC 1) (1; 9).

The diffusion of oxygen, which occurs in the pulmonary alveolus, to the tissues, is conditioned by the pressure gradient in the different levels at which gas exchange occurs. So, the decrease ofPIO₂ (partial pressure of inspired oxygen) adversely affects the rate of diffusion of oxygen from the pulmonary alveolus to pulmonary capillaries. That way there is a reduction in the percentage of the haemoglobin saturation and, consequently, less oxygen is transported to the tissues. As we ascend in altitude, the decrease of oxygen available for cellular metabolism complicates the permanence and performance of humans and has repercussions in various forms in the homeostasis of different biological systems (9).

The exposure to environments of hypobaric hypoxia induces numerous physiological adaptations, which tend to minimize the negative effect of reduced amount of oxygen available for the different tissues. Those adaptations occur in the respiratory system (dyspnea), circulatory system (hypertension, tachycardia), hormonal regulation (increase of erythropoietin) and hematologic components, among others (9).

The hypoxia symptoms depend on its severity. The primary symptoms include mental confusion, headache, fatigue, dyspnea, hypertension, tachycardia, a feeling of euphoria, hot and cold flashes and visual impairment. In severe hypoxia the victim changes in levels of consciousness, present cyanosis in all extremities (ears, lips, nose, fingers and toes), may present seizures and death may occur (6).

2.1.1.4. Frostbite

Frostbite is a condition resulting from excessive and continuous exposure of the skin to very low temperatures, causing the freezing of the tissues. When there is frostbite,
there is already hypothermia. Frostbite and hypothermia are both cold-related emergencies (10).

This condition has long been recognized. The oldest and most famous known case of frostbite and hypothermia is Ötzi, the pre-historic men discovered in the Chilean mountains, freeze during 5000 years. More recently, Napoleon's surgeon general, Baron Dominique Larrey, described for the first time the mechanism of frostbite, in 1812 during Napoleon's army retreat from Moscow. He also mentions the harmful effects of the freeze-thaw-freeze cycle suffered by the soldiers who would warm their frozen hands and feet over the campfire at night only to refreeze those same parts by the next morning. Frostbite was formerly a military problem, but today is also a civilian one as well, because the alpinism, as a sport, has been gaining more and more practitioners (1; 10).

Everyone is susceptible to frostbite, even those who live in cold climates most of their lives. The extremities of the human body (nose, ears, fingers and toes) are the most commonly affected (11).

Physiologically, the frostbite phenomenon happens when the exterior temperature decreases, the vessels contract and the skin becomes pallid. But when the skin is exposed to a temperature below 10ºC the superficial vessels of the skin dilate in order to warm up the extremity. It is possible to visualize this mechanism in action, when we see the redness of the nose, ears and hands, characteristic of cold weather. If the temperature continues to drop, the vessels begin to constrict and dilate intermittently, causing pain and throbbing. This pain is due to the toxic metabolites that are released in the contraction phase, when the tissues have no blood supply. However, these oscillations prevent that the intense cold damages the tissues and provides enough blood supply, although intermittent. If the temperature continuous to drop excessively the superficial blood vessels contracts continuously and the tissues temperature is balanced with the exterior temperature, causing frostbite (1; 9; 10).

Frostbite (FIG 2 and FIG 3) has four degrees (11):

- **First degree injury** - the first degree affects the skin surface causing pain, itching, numbness and the development of white, red, and yellow patches on the skin. This condition is commonly called of "frostnip". Frostnip does not usually cause permanent damage, because it is superficial. Although, long-term exposure may initiate the intermittent stage described above. These first degree injury symptoms are also called as Raynaud's syndrome (FIG 1).
FIG 1 – Red, blue and white fingers associated with Raynaud's phenomenon

- **Second degree injury** – when the frostnip is not immediately acted on, the skin may freeze and harden, but the deep tissues are not affected, they remain soft and normal. However, blister will occur 1-2 days after exposure. This phase is treatable with proper aid and care.

- **Third and Fourth degree injury** - if the skin area is exposed to extremely low temperature for a long time, deep frostbite happens. During these two phases, the skin, blood vessels, muscles, tendons and nerves may be permanently damaged. The skin becomes hard, feels waxy, and the use of the area is temporarily lost (in severe cases, use of the area is permanently lost). Extremities with deep frostbite can sometimes show areas of blood-filled blisters on the skin, which will become black. In extreme cases, frostbitten areas may need amputation, to prevent gangrene.
The consequences of frostbite may be severe and with limited capacity of recovery, therefore the prevention is essential. The first step to prevention is the ability to evaluate what is your limit, but it is also essential to have good protective equipment.

2.1.2. Metabolism Process

The human body may be considered to be a chemical engine, and food with different contents, the fuel. At rest, some chemical energy food is transformed into mechanical work. All this process is called metabolism.
Metabolism is the set of chemical and physical processes that occur within the cells of a living organism. These reactions are responsible for the processes of synthesis and degradation of nutrients in the cells, allowing the cells growth and multiplication. Metabolism is usually divided into two categories: Catabolism and Anabolism. Catabolism breaks down large molecules (polysaccharides, lipids, nucleic acids and proteins) into smaller parts (monosaccharide, fatty acids, nucleotides, and amino acids) releasing energy (ATP) that is used in cellular respiration and to produce heat to warm the body. Anabolism is powered by Catabolism. Anabolism construct molecules from smaller units and uses energy (ATP) to construct components of cells such as proteins and nucleic acids (tissues and organs) \(^{(5, 12)}\).

The body is always spending energy, and that energy is ultimately lost from the body in the form of heat. The balance of intake and loss is maintained during daily physical activity. The minimum energy expenditure is called basal metabolism, and is the necessary energy that the body uses, at rest, for the functioning of all organs (heart, brain, lungs, intestines, etc.). With an increase of physical activity there is an increase of metabolic heat production (ANNEX A) \(^{(12)}\).

**2.1.3. Arm Thermal Dynamic Behaviour**

Until this point it was made an individual analysis of the biological consequences of long-term exposure of the human body that is in low temperatures and high-altitude. However, all these consequences do not happen without influencing each other.

The human body, in terms of thermal dynamic, in extreme conditions (high-altitude and the low temperatures), will favour some of its areas, which will allow its survival. Dividing the body in three parts, it will prioritize the head, neck and torso, then the arms and legs and in last the extremities (ears, nose, fingers and toes). This order of importance is considered by the body to be the one that could ensure the functionality of the vital organs \(^{(1, 5)}\).

The human being is an animal unprepared to extreme temperatures. The invention of clothing made possible to the human being to live in some environments that were not possible if we were naked. This way the length of the arms and legs are adapted to mild conditions \(^{(1)}\).
For the purpose of this work, it will be considered a more detailed analysis of the arm. Anatomically the arms provide us a tool that allows the manipulation of the objects. In cold environments the arms acts as a cooler, due to its length and form\(^{(13)}\).

In high altitude the atmospheric pressure and temperature are low, making the relative humidity also low. The lower the atmospheric relative humidity, the greater the separation between the values of partial vapour pressure and saturation vapour pressure making the sweat pass more easily into a gaseous state. This phenomenon contributes to the dehydration of the body. During physical activity the body releases heat in the form of hot vapour to cool off. If that vapour condenses in the skin, the heat is transferred again to the body, giving the sensation of warm. However, at very low temperatures the hot vapour leaves the body and touch the clothing fabric, which has a lower temperature than the body, condensing. The condensed vapour will increase the thermal conduction of the fabric insulation, leading to a reduction of the inner temperature of the clothing. In conclusion, the thermal efficiency of the clothing is compromised\(^{(14;15)}\).

As the hot blood comes from the torso it cools down passing through the arm, returning to the torso again (FIG 4), contributing in lowering the body core temperature. This phenomenon contributes to the acceleration of hypothermia process\(^{(5)}\).

![FIG 4 - Blood circulation of the arm](image)

In High Mountain the body is in an environment with thin air, making the blood less saturated causing an inadequate oxygenation of the tissues. With the body in high-altitude dehydration inevitably happens. With dehydration the blood becomes thicker and flows more slowly (FIG 4). With the reduction of blood flow the cells receive less oxygen, reducing the cellular metabolism. Consequently less heat is produced, favouring the cooling of the arm. When the blood keeps returning to the torso, always
more cold than expected, the body defends itself starting peripheral vasoconstriction, to protect vital organs and minimize damage from hypothermia. If there was already a limited blood flow to the tissues, caused by dehydration, with the vasoconstriction caused by hypothermia, the tissues are even more deprived of blood (FIG 5). Combining all these events, frostbite is inevitable, if the cycle is not reversed (5; 9; 10).

![FIG 5 - Arm thermal dynamic scheme](image)

2.2. METEOROLOGICAL PARAMETERS

2.2.1. Relative Humidity

The relative humidity \((U)\) is a relation between the partial vapour pressure \((P_v)\) and saturation vapour pressure \((P_s)\) in the air \((16)\).

\[
U = \frac{P_v}{P_s} \tag{2-1}
\]
In perceptual form,

\[ U\% = \frac{P_v}{P_s} \times 100 \]  \hspace{1cm} (2-2)

### 2.2.2. Dew Point

When a portion of air that contains a constant amount of moister is gradually cooled down the air humidity will saturate, forcing the water to condensate. The temperature at which the moister will condensate is called Dew point. The dew point equation is deduced using the Magnus-Tetens formula \( (P_w) \) \(^{(17)}\).

\[ P_w = 6.11 \times 10^{7.5T/(237.3+T)} \]  \hspace{1cm} (2-3)

The dew point \( (T_d) \) can be also determined by the equation \(^{(18)}\),

\[ T_d (T, U) = \frac{b \cdot \alpha(T, U)}{a - \alpha(T, U)} \]  \hspace{1cm} (2-4)

Where,

\[ \alpha(T, U) = \ln(U) + \frac{a \cdot T}{b \cdot T} \]  \hspace{1cm} (2-5)

The parameter \( a \) and \( b \) represent the Magnus formula constants. Where \( a = 7.5 \) and \( b = 237.3 \).
2.3. HEAT TRANSFER

Energy can be transfer as heat from one system to another, as the result of temperature difference. The heat transfer is always made from de higher temperature body to the lower one. This mechanism stops when the same temperature is reached. Heat can be transferred in three different ways: Conduction, Convection and Radiation (18).

2.3.1. Conduction

When particles with different energy interact, the more energetic one will transfer energy to the less energetic one. This process is called Conduction (18).

The rate of heat conduction, through a surface, is conditioned by the shape, thickness and the temperature gradients in the material. The rate of heat transfer ($\dot{Q}$), through a plane wall, could be define by the equation (18).

$$\dot{Q}_{\text{cond}} = kA_s \frac{T_1 - T_2}{\Delta x} = -kA_s \frac{\Delta T}{\Delta x} \quad (W) \quad (2-6)$$

Where $A_s$ is the plane surface area, $\Delta T$ the difference between temperature of the surfaces of the plane, $\Delta x$ the thickness of the material and $k$ the thermal conduction coefficient, which is a property in each material (FIG 6) (18).

In the limit, ($\Delta x \to 0$), the equation (2-6) reduces to the differential form.

$$\dot{Q}_{\text{cond}} = -kA_s \frac{dT}{dx} \quad (W) \quad (2-7)$$
This equation is known as Fourier law of heat conduction.

![Diagram of heat conduction through a large plan wall](image)

**FIG 6** - Heat conduction through a large plan wall of thickness $\Delta x$ and area $A^{(18)}$

### 2.3.2. Convection

The heat transfer from a solid surface to a liquid or gas, in motion, is called Convection. The heat exchange between the solid surface and the fluid is enhanced by the fluid motion. Being in motion becomes more difficult to calculate the amount of heat exchange. There are two types of convection: the forced convection and natural convection. The forced convection is characterized by fluid motion originated by an external source, like a fan pump or the wind. The natural convection is the one originated by buoyancy forces that are induced by density differences due variations in the fluid temperature. The mathematical equation that describes the heat transfer by convection is called Newton’s law of cooling$^{(18)}$.

The rate of the convection heat transfer is proportional to the temperature difference, and is conveniently expressed as Newton’s Law of Cooling$^{(18)}$.

$$\dot{Q}_{\text{conv}} = h_{\text{conv}}A_s(T_s - T_w) \quad (W) \quad (2-8)$$
Where the $h_{\text{conv}}$ is the convection heat transfer coefficient, $A_s$ the area of the surface where the heat transfer occurs, $T_s$ the surface temperature and $T_\infty$ a temperature in the fluid sufficiently far from the surface. Convection heat transfer coefficient is not a specific property of a fluid. This parameter depends on the fluid properties, surface geometry and bulk fluid velocity\(^{(18)}\).

### 2.3.3. Thermal radiation

Thermal Radiation is the energy emitted by a body in the form of electromagnetic waves, at a determined temperature. The heat transfer by radiation is the fastest energy (at the speed of light), and do not requires an intervening medium to transfer energy, unlike conduction and convection. All bodies, at a temperature above absolute zero, emits thermal radiation\(^{(18)}\).

The rate of radiation that can be emitted from a surface, at temperature $T_s$, can be determined from the Stefan–Boltzmann law ($\dot{Q} = \sigma T^4$)\(^{(18)}\).

\[
\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \quad (\text{W}) \tag{2-9}
\]

Where the $\sigma$ is the Stefan-Boltzmann constant, $A_s$ the surface area and $\varepsilon$ the emissivity of the surface ($0 \leq \varepsilon \leq 1$).

Other important property is the absorptivity, $\alpha$. Absorptivity is a material characteristic that represents the fraction of radiation absorbed by a surface ($0 \leq \alpha \leq 1$). The rate that a surface absorbs radiation ($\dot{Q}_{\text{absorbed}}$) (FIG 7) is determined by\(^{(18)}\),

\[
\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \quad (\text{W}) \tag{2-10}
\]

Where $\dot{Q}_{\text{incident}}$ is the rate at which the radiation is incident on the surface.
The Kirchhoff’s law of radiation states that at a given surface temperature, the wavelength of the average emissivity is equal to the average absorptivity.

A surface $A_s$, at a absolute temperature $T_s$, with a emissivity $\varepsilon$, receives radiation from the surrounding at a determined temperature, $T_{surr}$. The rate of radiation heat transfers $\dot{Q}_{rad}$ between the surface and the surrounding is given by

$$\dot{Q}_{rad} = \varepsilon \sigma A_s (T_s^4 - T_{surr}^4)$$  \hspace{1cm} (2-11)

The previous equation can also be define is order of the heat transfer coefficient, $h_{rad}$,

$$\dot{Q}_{rad} = h_{rad} A_s (T_s - T_\infty)$$  \hspace{1cm} (2-12)

### 2.3.4. Thermal Resistance Concept

Thermal resistance is a mathematical model established to simplify the heat transfer calculation. That model has a macroscopic approach of the heat transfer dynamics, creating a concept of thermal resistance, i.e., capability to a medium resist to the heat transfer.

The thermal resistance can be define by,

$$R = \frac{T_1 - T_2}{\dot{Q}}$$  \hspace{1cm} (2-13)
By rearranging the equations (2-6), (2-8) and (2-11), can be defined the conduction resistance \( R_{\text{cond}} \), the convection resistance \( R_{\text{conv}} \) and the radiation resistance \( R_{\text{rad}} \).

For defining the conduction resistance, where \( L \) is the thickness of the material,

\[
\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{L} = \frac{T_1 - T_2}{R_{\text{cond}}} \tag{2-14}
\]

\[
R_{\text{cond}} = \frac{L}{kA} \tag{2-15}
\]

The convection resistance,

\[
\dot{Q}_{\text{conv}} = h_{\text{conv}} A_s (T_s - T_\infty) = \frac{T_s - T_\infty}{R_{\text{rad}}} \tag{2-16}
\]

\[
R_{\text{conv}} = \frac{1}{h_{\text{conv}} A_s}
\]

and The radiation resistance,

\[
\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) = \frac{T_s - T_{\text{surr}}}{R_{\text{rad}}} \tag{2-17}
\]

\[
R_{\text{rad}} = \frac{1}{h_{\text{rad}} A_s}
\]

In analogy the thermal resistance behaves as electric resistor, the series and parallel arrangements of resistances are treated in the same way.

\[
R = R_1 + R_2 + \cdots + R_n \quad \text{(series)} \tag{2-18}
\]

\[
\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \quad \text{(parallel)} \tag{2-19}
\]
2.4. PROCESS CONTROL

Process control is a group of techniques, with the purpose of accomplish and maintain a desired state, responding to any exterior changes.

To control a process, the desired set point (SP), must be compared with the process output value (PV). The difference between those values is the error (E), which shall be minimized by the controller (Fig 8).

\[ E = SP - PV \]  \hspace{1cm} (2-20)

![Process control diagram](image)

**FIG 8 – Process control diagram**

### 2.4.1 Proportional controller \((P_{output})\)

The proportional controller actuate over the error by respond proportionally to the error,

\[ P_{output} = K_p E(t) \]  \hspace{1cm} (2-21)

Where, \(K_p\) is the proportional gain.

In a system with losses, in order to the output converge to a fixed value, the energy must equals the losses, so the proportional controller, will, in this case, stabilize in a value different than the set point.
2.4.2 Integrative controller ($I_{output}$)

The integrative controller will sum the error over time, increasing the action on the process variable. This value should converge to the setpoint due to losses.

$$I_{output} = K_i \int_0^t E(t) \, dt$$  \hspace{1cm} (2-22)

The integrative controller will always pass over the set point value (overshoot), the action on the process will only be reversed when the sum of the negative error equals the sum of the positive errors. The integral gain ($K_i$) will determine the level of overshoot.

2.4.3 Derivative controller ($D_{output}$)

The derivative controller ($D_{output}$) is a controller that responds to the changes of the error value. This controller has a fast reaction to rapid changes in the system (set point and process values).

$$D_{output} = K_d \frac{\partial E(t)}{\partial t}$$  \hspace{1cm} (2-23)

Where, $K_d$ is the derivative gain.

2.4.4 PID Controller

The PID controller (proportional, integrator and derivative), combine the tree previous controllers (Fig 9) in order answer to the problems of each.
The integrative controller used will resolve the problem of the proportional controller offset. The derivative controller will predict the evolution of the process increasing its action on rapid error changes. That way it reaches the set point quicker, making the integrative controller action on the process less relevant, and reducing the debouncing effect. The proportional controller, because its action is always directed to the set point, will help the process output to converge quicker.

The PID controller output \( M \) can be defined by the equation (x-x)

\[
M = K_p E(t) + K_i \int_0^t E(t) \, dt + K_d \frac{\partial E(t)}{\partial t}
\]  

(2-23)
3. STA1 OVERVIEW

The STA Project pretends create a complete suit solution that provides a safer journey to Alpinism practice above 7000m.

In the first phase of STA Project, it is intended to study and develop a hi-tech mitt that will have an active heat control, so that high altitude alpinism could be a better experience. The high-tech mitt is composed by two main parts: the mitt itself, and an electronic thermal control system.

During the climbing of the mountain, symptoms related with the ascent and the low temperatures appear gradually and the heat dissipated by the hand reduces. Consequently it is created a gap between the optimal temperature (set point temperature) and the natural temperature inside the mitt (temperature inside the mitt without the usage of any control system). If the temperature rises, there will be an increase of perspiration, increasing the dehydration, and if the temperature becomes too low, there will increase the vasoconstriction effect. It is in this stage that the electronic control system will act as a body temperature stabilizer. The usage of a temperature control system can reduce the settlement velocity of the symptoms, reducing the risk of frostbite condition.

The professional alpinist João Garcia had an important role in the decisions made. He reported the problems that he faced and pointed aspects that can lead to the success of this application.

All the calculus and considerations for the design of the mitt solution were made for an altitude of 8000m, an exterior temperature of $-30^\circ C$ and a wind of 10m/s.
4. MATERIALS

Today’s alpinism equipment (apparel and mitt) consists of a simple structure, normally composed by an outer layer of resistant fabric, a lining of polyester fibber and between those, two layers of filling plumes, making the equipment very light. One of the major problems of this equipment is that the thermal isolation is guaranteed by air space, so when compressed the isolation is lost, making the alpinist lose a large quantity of body heat.

At high altitude the environment temperature is very low. This environmental factor has an effect on air humidity. The humidity levels become very low, because at very low temperatures the water turns into snow.

4.1. MULTILAYER INSULATION STRUCTURE

In 1895 the explorers Fridtjof Nansen and Hjalmar Johansen went to an expedition to the North Pole. They were lost, due to the movement of the polar cap, but survived in the polar circle for four months, twice the time originally planned. At the time they were trying a new strategy to fight the arctic cold, a multi layer insulation structure, and with their unexpected adventure they prove its effectiveness (19).

The multilayer structure insulation proved to be more efficient then the insulation materials used until then (wool, animal skin, etc.) due to the presence of air between each layer (“dead air”). That air difficult the air flow inside the insulation structure, preventing the heat to escape. Other positive aspect is the thermal contact resistance (FIG 10), i.e., the heat conduction through the layers reduces due to the imperfect thermal contact.
4.2. VAPOUR BARRIERS

Since Alpinism became a sport, the number of athletes has increased, making their personal experiences and stories a contribution to the understanding high mountain environments. One of the strategies used by the alpinists to increase insulation is the vapour barriers. Usually a vapour barrier is made with a simple plastic bag and its purpose is to maintain the humidity inside the mitt.

Inside of the insulation material normally used, there is a gradient of temperature from the inner to the outer temperature. As the vapour passes through the material, it cools down, condensing into water and ice. Because the thermal conductivity of the water is ten times higher than the conductivity of the insulation materials, the heat will be conducted mostly by the water and insulation efficiency is compromised.
4.3. PROPOSED SOLUTION

The proposed solution consists in a five layer structure (FIG 11). Each layer has a different function and the ensemble should answer to the insulation needed for high mountain environment.

![Figure 11 - Mitt material structure](image)

**Layer 1** – layer to protect the inner layers from the water and wind, as well as possible damages;

**Layer 2** – layer with the purpose of protecting the more inner layers from the cold;

**Layer 3** – layer with the purpose of stopping the water vapour of entering the second layer;

**Layer 4** – layer that provides air space and a medium for the electronic control system;

**Layer 5** – layer made with a material capable of making moisture management, in order to lower the amount of humidity in the mitt.
4.4. TYPES OF MATERIALS

4.4.1. Water Proof Fabrics (Layer 1 and 3)

In the high altitude environment the air is very dry, and the temperature is always below the freezing point. The selected fabric should be totally impermeable and light, there is no need for an expensive fabric with a complex structure. The TABLE 3 shows some of the available materials in the market.

<table>
<thead>
<tr>
<th>Material</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordura® UltraLight Fabric</td>
<td>Resistance to tears, scuffs and abrasion.</td>
</tr>
<tr>
<td></td>
<td>High tenacity filaments</td>
</tr>
<tr>
<td></td>
<td>Light</td>
</tr>
<tr>
<td>GORE-TEX®</td>
<td>Moister vapour escapes</td>
</tr>
<tr>
<td></td>
<td>Rain snow and wind stay out</td>
</tr>
<tr>
<td>Polyester Rip Stop Fabric</td>
<td>Water Resistant</td>
</tr>
<tr>
<td></td>
<td>Not breathable</td>
</tr>
<tr>
<td></td>
<td>Light weight</td>
</tr>
<tr>
<td>NanoSphere®</td>
<td>Water and dirt repelling</td>
</tr>
<tr>
<td></td>
<td>Light weight</td>
</tr>
<tr>
<td>3XDRY®</td>
<td>Water and dirt repelling</td>
</tr>
<tr>
<td></td>
<td>Absolve interior humidity</td>
</tr>
<tr>
<td>FluoroFree™</td>
<td>Water and dirt repelling</td>
</tr>
<tr>
<td></td>
<td>Light weight</td>
</tr>
<tr>
<td></td>
<td>Bluesign® standard</td>
</tr>
</tbody>
</table>

TABLE 2 - Waterproof materials available

The fabric selected for the layers 1 and 3, of the mitt, was the Polyester Rip Stop Fabric Zero Porosity (FIG 12).
Rip Stop Fabric has the feature of being made with a special reinforcing technique. This technique consists of creating a mesh with strategic strong points that prevent the fabric of tearing or ripping itself. There are several types of Rip Stop and for this project it will be considered only the one that has zero porosity. Rip Stop Fabric with zero porosity is made with very thin fibers and a tight weaving. This way, it becomes even lighter and absolutely waterproof. The application of Rip Stop Fabric is commonly seen in parachutes and hot air balloons.

The colour of the Rip Stop is in one side black and in the another silver (FIG 13a), these colours were chosen because the black is a colour that absorbs radiation and silver is a colour that reflects radiation (FIG 13b); a part of the absorbed radiation is transferred by conduction through the fabric and then radiated by the silver side (i); in the opposite direction the radiation is reflected by the silver surface maintaining the inner heat (ii).
This principle is used in the satellite insulation, because in space all the heat transfer is made by radiation.

4.4.2. Insulation materials (Layer 2)

To measure the insulation effectiveness of the products, the fabric insulation manufactures frequently use units like the thermal conduction coefficient (k) and the clo value, unit used to measure the thermal effectiveness of the clotting insulation (TABLE 3).

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>clo/g</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primaloft one</td>
<td>6,6</td>
<td>0,027</td>
<td>0,036</td>
</tr>
<tr>
<td>Primaloft sport</td>
<td>5,3</td>
<td>0,023</td>
<td>0,053</td>
</tr>
<tr>
<td>Cabot® Thermal Wrap</td>
<td>70,0</td>
<td>0,005</td>
<td>0,019</td>
</tr>
<tr>
<td>Thinsulate™ Type C</td>
<td>15,0</td>
<td>0,012</td>
<td>0,036</td>
</tr>
<tr>
<td>Spaceloft</td>
<td>150,0</td>
<td>0,003</td>
<td>0,013</td>
</tr>
</tbody>
</table>

TABLE 3 – Insulation materials available

The selection of the insulation material is not a simple task, because usually the fabric insulation manufactures present the information about thermal efficiency in a way that enhances their products to the buyer, making difficult to compare different insulation materials. For example, some of them present the only the clo value, and others only the k value.

A naked person has a clo value of zero and a typical business suit has one clo of insulation. The total clo value of a suit is the sum of all individual clo values of individual garment worn\(^{(18)}\).

Clo can be also define in order of the thermal resistance, \( R, \left( \frac{m^2 K}{W} \right) \)
The natural choice would be selecting the material with the highest thermal conduction coefficient \(k\). The fabrics with the highest \(k\) value were the Aerogel fabrics (Cabot\textsuperscript{©} Thermal Wrap and Spaceloft).

Aerogel material is the lightest and most insulating material on earth, so it would be a logical choice, but Aerogel material is a brittle material. Therefore, the Aerogel fabric is composed by a support fabric coated with Aerogel material, minimizing the damage in the Aerogel in the fabric. When the Aerogel cracks it becomes dust and fell out the fabric, so the amount of Aerogel material in the fabric reduces, losing its thermal efficiency. The Support fabric is a non woven fabric with a low compression coefficient, but makes it heavier.

The weight is a very important factor in Alpinism. So, although we could provide enough insulation with a thin Aerogel fabric, it still would be heavier than other solutions available in the market, and the Aerogel fabric will always require a fabric capable of containing the loosed particles, in order to prevent the inhalation of them by the alpinist. To analyze correctly which insulation material would be more appropriate, three parameters were considered: the density of the material, the Clo of fabric and the \(k\) value. Analysing the weight needed to assure 1clo of insulation per square meter, the material that can provide the best amount of insulation with less impact on the overall weight is the Primaloft One (TABLE 4).

\[
1 \text{ clo} = 0.155 \times \frac{m^2 K}{W}
\] (4-1)

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (g) to achieve 1clo of insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primaloft one</td>
<td>37,0</td>
</tr>
<tr>
<td>Primaloft sport</td>
<td>43,5</td>
</tr>
<tr>
<td>Cabot\textsuperscript{©} Thermal Wrap</td>
<td>200,0</td>
</tr>
<tr>
<td>Thinsulate\textsuperscript{™} Type C</td>
<td>83,3</td>
</tr>
<tr>
<td>Spaceloft</td>
<td>294,1</td>
</tr>
</tbody>
</table>

**TABLE 4** - Mass (g) to achieve 1clo of insulation, for each insulation material
In sum, because the application must be the lightest possible and the volume is not a problem, was chosen the Primaloft One.

4.4.3. Spacer Fabrics (Layer 4)

Spacer Fabrics (FIG 14) are woven fabrics with the purpose of creating a layer of air between the other fabrics structures, providing cushioning and an optimal air flow. With this fabric, the heated air will be distributed throughout the hand and not only for the portion of the hand near the heater. The air space created will also provide an extra insulation layer and prevent the total compression of the fabrics. When the insulation is compressed the quantity air reduces, making the heat conduction through the insulation much lower. The air space provided by spacer fabric in this layer will create a medium where the electronic control system can operate properly.

![Spacer fabric](image)

FIG 14 – Spacer fabric

4.2.1. Lining Fabrics (Layer 5)

For the layer 5 were considered fabrics that claimed to enhance the comfort (TABLE 5). Layer 5 will be placed in a worm and humid environment, where the temperature will be controlled by the electronic system, not requiring the usage of phase change material.
<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolmax®</td>
<td>Breathable, Dries quickly, Soft, Moister wicking</td>
</tr>
<tr>
<td>Outlast®</td>
<td>Phase change material, Light weight, Soft, Breathable Space certificate technology</td>
</tr>
<tr>
<td>Comfortemp®</td>
<td>Phase change material, Light weight, Soft, Breathable</td>
</tr>
<tr>
<td>Thermolight</td>
<td>Warmth, Soft, Comfortable, Light weight, Moister wicking</td>
</tr>
<tr>
<td>SCHOELLER®-PCM™</td>
<td>Phase change material, Breathable, Soft, Moister wicking</td>
</tr>
<tr>
<td>ENERGEAR™</td>
<td>Reflects a body's Far Infrared Rays (FIRs), Soft</td>
</tr>
</tbody>
</table>

**TABLE 5 – Lining fabrics available**

The purpose of this layer is to manage the moisture in order to lower the amount of humidity in the mitt. The lining fabric will be placed near the hand where there is an excess of humidity. The hand inside the mitt is always releasing heat. That heat passes through the layers of insulation in the mitt (FIG 15), creating a temperature gradient in the structure. Because the layer 3 (waterproof fabric) will act as a vapour barrier, the humidity present in layers 3, 4 and 5 will be high. Due to the high humidity level the fabric temperature easily matches the dew point temperature (GRAPHIC 2), condensing the water.
Therefore, is important to have a fabric that can provide a good moister wicking, offering good comfort and maintaining the hand warm.
4.5. HEAT TRANSFER CALCULATIONS

Although the alpinist is fitted with the electronic control system that controls the temperature, there is always the possibility of a system failure. So the mitt must have the minimum insulation to protect the alpinist from the dangers of the High Mountain.

Determine the amount of material needed to insulate any equipment in High Mountain is not easy. During the climbing, the atmospheric temperature is always changing, as well the performance of the human body. Predict the heat dissipation through the arms during the climbing is difficult too. The heat rate generated by the harms is different from the core, and will reduce over time. The mitt was designed to be used in the last stage of a High Mountain climbing. In that stage the alpinist will be in a physiological state difficult to predict, because organically each person responds differently, in terms of speed of settlement and severity of symptoms. Two alpinists, who are at the same altitude, at the same time, do not have the same heat loss rate, and during the climbing that value decreases, because the body starts its mechanisms of reaction to the altitude and cold (hypothermia, dehydration, etc.).

For simplification of the calculus of the heat transfer in the mitt insulation, they will be made for a plane surface. That way the error is made by excess.

A low weight in the complete mitt solution (mitt + electronic control system) is a very important factor to have in mind, because the alpinist make sure he carries the lightest equipment possible during the climbing, and the weight factor will determinate the acceptance of the mitt in the alpinism community.

4.5.1. Calculus of the heat flux

The body temperature is maintained by continuous metabolism losses. Considering the thermal comfort, those losses can be divided in sensible heat losses: convection (C), radiation (R), conduction (K), sensible respiration (L); and latent losses: vapour diffusion (E_{diff}), evaporation of regulatory sweating (E_{rsw}) and respiration latent losses (E_{resp}).
The equation that establishes the mechanisms related to thermal comfort is (21),

\[ H - (E_{diff} + E_{rsu} + E_{resp}) - L = K = C + R \]  

Where \( H = M - W \), being \( H \) the heat balance, \( M \) the metabolic heat, and the \( W \) the metabolic rate converted into work.

The values of latent losses are not considered for thermal insulation calculations; the reason is because those losses came from a water phase change (liquid to vapour). Considering that the quantity of condensed water in the mitt will stabilize, the flux of vapour that is expelled from the mitt will be equal to the vapour expelled from the body, so, the latent energy will be lost. The sensible respiration losses are not considered for the insulation because the heat is expelled directly from the mouth. In the skin surface, it will be considered only the losses by radiation and convection.

For the insulation calculus it was considered the metabolic rate of a man walking up a grade of 5% inclination, at 0.45 m/s in the standing position (\( M = 139W/m^2 \) and \( = 0.07 \) ) (ANNEX A).

\[ W = M \times \eta \]  

\[ W = 139 \times 0.07 = 9.73W/m^2 \]

Where \( \eta \) is the mechanical efficiency.

For knowing the \( C + R \) value the other elements of the equation (4-2) must be determined:

- **Vapour pressure \( (P_v) \)**

Considering a ambient temperature \( (T_a) \) of \(-30^\circ C\) and a relative humidity of 0.3 (typical value in High Mountain environment, 8000m, during expedition), the saturation vapour pressure can be calculated by the Magnus Tetens equation,
\[ P_s = 6.11 \times e^{7.5 T_a/(237.3+T_a)} = 50.2 \text{ Pa} \] (4-4)

From the relative humidity relation (2-1),

\[ U = \frac{P_v}{P_s} \Leftrightarrow P_v = P_s \times U \]

\[ \Leftrightarrow P_v = 50.2 \times 0.3 \]

\[ \Leftrightarrow P_v = 15.1 \text{ Pa} \]

- \( E_{\text{diff}} \) – Heat loss due to vapour diffusion through the skin \(^{(22)}\)

\[ E_{\text{diff}} = 3.05 \times 10^{-3} \times (5733 - 6.99 \times H - P_v) \]

\[ E_{\text{diff}} = 14.68 \text{ W/m}^2 \] (4-5)

- \( E_{\text{rswe}} \) – Heat loss due to evaporation of regulatory sweating from the skin \(^{(22)}\)

\[ E_{\text{rswe}} = 0.42 \left( (H) - 58.15 \right) \]

\[ E_{\text{rswe}} = 29.87 \text{ W/m}^2 \] (4-6)

- \( E_{\text{resp}} \) – Heat loss respiration latent heat loss \(^{(22)}\)

\[ E_{\text{resp}} = 1.7 \times 10^{-5} \times M(5867 - P_v) \]

\[ E_{\text{resp}} = 13.83 \text{ W/m}^2 \] (4-7)
• $L$ – Sensible (dry) heat loss, respiration \(^{(23)}\)

\[
L = 0,0014 \times M \times (34 - T_a) \tag{4-8}
\]

\[
L = 12,45 \text{ W/m}^2
\]

After gathering all the equation (4-2) values, the $C + R$ can be know calculated,

\[
C + R = 129,27 - 14,68 - 29,87 - 13,83 - 12,45
\]

\[
C + R = 58,43 \text{ W}
\]

In this case,

\[
\dot{Q} = C + R \tag{4-9}
\]

The $C + R$ value represents the heat flux ($\dot{Q}$) through the fabric structure (FIG 16)

FIG 16 - Equivalent heat resistance at the surface of the clothing
The heat resistance from the exterior of the clothing \((R_{\text{ext}})\), in this application, can be defined in three different ways,

\[
R_{\text{ext}} = \frac{R_{\text{conv}} \times R_{\text{rad}}}{R_{\text{conv}} + R_{\text{rad}}} \quad (4-10)
\]

\[
R_{\text{ext}} = \frac{T_{\text{cl}} - T_{\infty}}{Q} \quad (4-11)
\]

\[
R_{\text{ext}} = \frac{1}{h_{\text{comb}}} \quad (4-12)
\]

Where,

\[
h_{\text{comb}} = h_{\text{rad}} + h_{\text{conv}} \quad (4-13)
\]

Combining the previous equations (4-11 and 4-12) the clothing temperature can be determined,

\[
T_{\text{cl}} = \frac{\dot{Q}}{h_{\text{rad}} + h_{\text{conv}}} + T_{\infty} \quad (4-14)
\]

In an iterative process using the equations (4-14), (4-15), (4-16), (4-17) and (4-18) was determined the value of \(T_{\text{cl}} = -28.59^\circ\text{C}\).

- **Convection \((C)\)**

\[
h_{\text{conv}} = 12.1 \times \sqrt{V} \quad (4-15)
\]

\[
h_{\text{conv}} = 38.26 \text{ m}^2.\text{°C/W}
\]
Where $h_{\text{conv}}$ is the convection heat transfer coefficient \(^{(13)}\) and $V$ the wind velocity \((10\text{ m/s})\). To calculate the Convection it will be used the equation (4-16) \(^{(23)}\)

\[
C = h_c (T_{cl} - T_a)
\]  
\[
C = 54,02 \text{ W/m}^2
\]

- **Radiation (R)**

\[
h_{\text{rad}} = \varepsilon \times \sigma \times (T_{cl}^2 + T_a^2)(T_{cl} + T_a)
\]  
\[
h_{\text{rad}} = 3,12 \text{ m}^2\cdot\text{K/W}
\]

Where $h_{\text{rad}}$ is the radiation heat transfer coefficient \(^{(18)}\) and $\varepsilon$ the emissivity (0,95), and $\sigma$ the Stefan-Boltzmann constant.

\[
R = h_{\text{rad}}(T_{cl} - T_a)
\]  
\[
R = 4,41 \text{ W/m}^2
\]

### 4.5.2. Calculus of the insulation thickness of the mitt (general)

In an expedition the climbers use a pair of gloves inside the mitt to perform more complex tasks like use an ice axe, drink water, eat, etc. For that reason, in the insulation calculus, it will be considered a pair of gloves made of Polartec Classic fabric, with 3mm.

Analysing the mitt fabric structure it was decided of not considering the layers 1, 3 and 5 to the insulation calculus, because their influence on the final result is negligible, due to their characteristics, like a thin thickness (a fraction of a millimetre), and a $k$ value much higher than usual $k$ value of the other materials.
The calculus presented below concern the insulation of the mitt in general (FIG 17), with exception of the palm area which will be calculated after.

**FIG 17 - Mitt insulation structure scheme (general)**

- **Calculus of the total resistance** \( R_{total} \)

The total thermal resistance is equal to the sum of the partial resistance.

\[
R_{total} = R_1 + R_2 + R_3 + R_4
\]  

(4-19)

And can also be defined as,

\[
R_{total} = \frac{T_{Skin} - T_{\infty}}{Q} \Leftrightarrow R_{total} = \frac{34 - (-30)}{58.43}
\]

(4-20)

\( \Leftrightarrow R_{total} = 1.10 \, \text{m}^2 \cdot ^\circ \text{C}/\text{W} \)
The values of the skin temperature and the exterior temperature are 34°C and −30°C, respectively.

- **Calculus of the resistance one** \((R_1)\)

  The first material is the Polartec classic fabric that has a \(k = 0.023 \text{ W/mK}\) and a material thickness \((L_1)\) of 3 mm.

  \[
  R_1 = \frac{L_1}{k_1}
  \]

  \[
  R_1 = 0.13 \text{ m}^2\cdot\text{°C/W}
  \]

- **Calculus of the resistance two** \((R_2)\)

  This layer has the spacer fabric, to simplify the calculus it will be considered as an air layer. The air has a \(k\) value of 0.026 \(\text{ W/mK}\) and a \(L_2 = 0.005 \text{ m}\)

  Applying the equation \((2-14)\),

  \[
  R_2 = \frac{L_2}{k_2}
  \]

  \[
  R_2 = 0.19 \text{ m}^2\cdot\text{°C/W}
  \]

- **Calculus of** \(T_2\) **and** \(T_3\)

  Using the concept of thermal resistance, equation \((2-13)\), the temperature at the fabric surface can be calculated,

  \[
  T_x = T_{x-1} - \frac{Q \times L_{x-1}}{k_{x-1}}
  \]

  \[
  T_2 = 26.38\text{°C}
  \]

  \[
  T_3 = 15.14\text{°C}
  \]}
\( T_4 \) was already calculated \( T_4 = -28.59^\circ C \)

- **Calculus of the resistance four (\( R_4 \))**

The resistance four (\( R_4 \)) is composed by the parallel of the convection and the radiation resistance (FIG 16)

\[
R_4 = \frac{1}{h_{comb}} \tag{4-23}
\]

\( R_4 = 0.024 \text{ m}^2 \text{ °C/W} \)

- **Calculus of the resistance three (\( R_3 \))**

After gathering all the resistance values, the \( R_3 \) can be determined by the equation (4-19)

\[
R_3 = R_{total} - R_1 - R_2 - R_4
\]

\( R_3 = 0.75 \text{ m}^2 \text{ °C/W} \)

- **Calculus of the \( L_3 \)**

The undefined thickness value of insulation is \( L_3 \). This layer insulation thickness will determinate the overall mitt insulation thickness.

The pretended insulation value can be determined through the equation (2-15),

\[
L_3 = R_3 \times k
\]

\( L_3 = 0.027 \text{ m} = 2.7 \text{ cm} \)

Were the \( k \) value for the Primaloft One is 0.036 \( \text{ W/mK} \)
4.5.3. Calculus of the insulation thickness of the mitt (palm area)

The palm of the hand is an area that is frequently used to grab objects, so the insulation material is compressed, losing its insulations characteristics. For that reason it became necessary include the Thermal Wrap insulation fabric in the palm area (FIG 18), because this fabric maintains its characteristics when compressed.

The Thermal Wrap fabric is a very good insulation material, more insulate than any of the other fabrics used in the mitt, and this factor will make the overall thickness of the insulation in the palm area thinner than in the rest of the mitt.

Some of the resistance and temperature values were calculated previously (4.5.2.), however with different nomenclature, resulting for this particular case as:

\[
R_1 = 0,13 \text{ m}^2 \cdot \text{°C/W} \quad R_2 = 0,19 \text{ m}^2 \cdot \text{°C/W} \quad R_5 = 0,024 \text{ m}^2 \cdot \text{°C/W}
\]

\[
T_1 = 34^\circ \text{C} \quad T_2 = 26,38^\circ \text{C} \quad T_3 = 15,14^\circ \text{C} \quad T_5 = -28,59^\circ \text{C}
\]

- **Calculus of the** $R_3$

The Thermal Wrap fabric chosen has a $k = 0,019 \text{W/m.K}$ and a thickness of $L_3 = 4 \text{mm}$
\[ R_3 = \frac{L_3}{k_3} \quad (4-24) \]
\[ R_3 = 0,21 \text{ m}^2 \text{C/W} \]

- **Calculus of the** \( T_4 \)

Applying the equation \((4-22)\), \( T_4 = 2,84 \text{ °C} \)

- **Calculus of the** \( R_4 \)

After having \( R_{total}, R_1, R_2, R_3 \) and \( R_5 \) the resistance values calculated, \( R_4 \) the can be determinate,

\[ R_4 = R_{total} - R_1 - R_2 - R_3 - R_5 \quad (4-25) \]
\[ R_4 = 0,54 \text{ m}^2 \text{C/W} \]

- **Calculus of the** \( L_4 \)

The undefined thickness value of insulation is \( L_4 \). This layer insulation thickness will determinate the overall mitt insulation thickness.

For the palm area insulation the Primaloft One material has a thickness determined by the equation \((2-15)\),

\[ L_4 = R_4 \times k_4 \quad (4-26) \]
\[ L_4 = 0,54 \times 0,036 = 0,019 \text{ m} = 1,9\text{cm} \]
5. ELECTRONIC SYSTEM DEVELOPMENT

Alpinism is a sport practiced in a very harsh and demanding environment. During workout it is easy to feel high oscillations in the temperature, due to the heat dynamics of the human body. That is why it is important to have a temperature control system to compensate these oscillations and reduce the losses by minimizing the body physiologic responses (sweat and vasoconstriction).

The solution found to control temperature was an electronic device that can respond to the temperature changes inside the mitt.

The proposed electronic device is not the same for the two mitts, because there is a higher percentage of right handed people, the human machine interface (HMI) is placed only in one of the mitts. The HMI is placed in the left mitt in order to be operated by the right hand.

The left mitt electronic device is composed by a microcontroller, human machine interface (HMI) and a sensing, actuator and communication module (FIG 19). The right mitt electronic device does not need the HMI module, the control parameters should be transferred by the communication module.
5.1. HUMAN MACHINE INTERFACE (HMI)

The HMI is used by the user to interact with the embedded system. In this project it is mandatory that the user of the mitt has the possibility of choose the desired application parameters (set point and display contrast).

The HMI is composed by a display and a keyboard (FIG 20). The microcontroller will process the information, when the user push the button in the keyboard, and it will show on the display the operational input, as well as additional information, like: exterior temperature, interior mitt temperature and battery state.
5.1.1. Display

The display used was a Colour Nokia LCD $128 \times 128$ (FIG 21). This display requires: two power inputs (one with $3.3V$ for the logic circuits and other with $7V$ for the backlights) and a 9 bits SPI communication (1 bit to indicate data type and the other 8 bits for data transmission). This LCD has a minimum operating temperature of $-20^\circ C$, but the Project has a specification requirement of $-30^\circ C$. So this LCD will not be used to the final product. However, this was the display used in this stage of the Project because it was available in the company and the size is suitable for the future final product, making easy the change to a similar model with the required specifications.
5.1.2. Keyboard

For entering data was chosen the Fibretronics™ Connected Wear Linear Keypad (FIG 22). This keyboard was designed to be used in apparel applications. It has 5 buttons and offers a good support area, maintaining the button in the right place while pressing. This keyboard is also flexible, waterproof and can be sewed. It has a temperature operation range of $-30^\circ C$ to $80^\circ C$ and weights $20g$.

![Fibretronics™ Connected Wear Linear Keypad](image)

**FIG 22** - Fibretronics™ Connected Wear Linear Keypad

The function principle of the keyboard is represented in the FIG 23. It is composed by an array of resistors and push buttons. All the resistors have different values, so when a button is pressed the respective resistor is suppressed from the circuit, making the value read by the microcontroller ADC different for each button. This way it can be determinate the operation chosen by the user.

![Keyboard scheme](image)

**FIG 23** - Keyboard scheme
5.1.3. Visual Arrangement and Functionality

The HMI visual interface was designed considering the state of hypoxia (mental confusion) that the alpinist will potentially face.

The HMI visual interface has two menus: one shows the information regarding the functioning of the system (Menu 1), and the other shows the options to configure the visor contrast (Menu 2). Both menus were designed to be the simplest possible, favouring the usability of the system. Those menus are accessed by the keyboard to interact with the system.

When the system is turned on it starts with the Menu 1. In the Menu 1 (FIG 24) the user can see information regarding the exterior temperature, the left and right mitt temperature, the control set point, the left and right battery state, and the charging state. The most important parameter is the set point, so, it is presented in big numbers; the temperature indicators have images showing what temperature is being read (exterior, left mitt, right mitt); the left mitt temperature indicator is presented more to the left, being read first, making easier to associate with the mitt that have the HMI interface. For the battery state bar this same principle is used. In the bottom left of the display there are two circles that indicate the charging state.

When the indicator present the colour black, no power input is detected. If the circle is twinkling between black and blue the battery is charging, and if the circle presents the colour green, the charge is complete (FIG 25).
The keyboard has five buttons (FIG 26): two for contrast set, one for turning the light on, and two for adjusting the control set point.

When a button is clicked the backlight is turned on, the HMI is programmed this way to make it easy to operate. After a few seconds without pressing any button the light turns off.

To change the set point the user just need to click in the \(-\) buttons. In the keyboard the buttons also have a red and blue colour to indicate that the choice will increase (red) or decrease the temperature (blue).

The light button (\(\bigcirc\)) can turn the light ON without interfering with any parameter, but it has an additional function: when pressed for a period of time (6 seconds) it gives access to the Menu 2 (FIG 27). The reason for this kind of access is because the Menu 2 is a configuration menu (contrast), and accessing it should not be accidental. The Menu 2 gives the possibility of defining the contrast of the screen by clicking in the contrast buttons on the keyboard (\(\bigcirc\)). The buttons \(-\) and \(\bigcirc\) have a similar
function (increase or decrease), it was chosen make them different because that way the user associate a visual image to a function, reducing the number of options, taking much less time to make a decision\(^{(24)}\).

The Menu 2 shows the contrast value of the moment in big numbers; in the bottom there are rectangles with all the colours available in the HMI interface. Having all the colours available on screen is easier to see the behaviour of the colours in the selected contrast (FIG 27). When the Menu 2 is not used for more than 6 seconds it returns to the Menu 1.

![Contrast Menu](image1)

**FIG 27 - HMI Menu 2**

### 5.1.4. HMI Software Implementation

The LCD selected has three modes of specifying a pixel's colour: 8, 12, or 16 bit. The simplicity of the menus makes it not necessary to have a high number of colours available, so, the 8 bit colour mode was chosen. The images are stored as a single line array. In that array are stored an 8 bit the data regarding each pixel colour. The 8 bit colour is sent by a 9 bit package (1 bit for data type and 8 bits containing RGB information of the pixel colour) (FIG 28).

![RGB Package](image2)

**FIG 28 - LCD RGB package**
The memory of the chosen microcontroller was not big enough to save all the big regular size images (e.g. the set point and contrast indicator numbers). The solution for this problem was the implementation of a custom type image, smaller in size. Because the images only have two colours (foreword and background colours) the new image type does not contain information regarding the pixel colour, it contains the information when the colour of the pixel changes. The software can read the information contained in each array cell and count the number of pixels.

The implementation in software of the features presented in “Visual arrangement and functionality” can be viewed in the HMI workflow (FIG 29)
5.2. TEMPERATURE SENSOR

The temperature range of the thermometer should be between $-40^\circ C$ and $40^\circ C$. This is not a very demanding range, the majority of the thermometers in the market are ready to operate in this temperature range. It is easy to find a low cost solution with good accurate measures.

The chosen thermometer is the ADT75. It is an on-chip temperature sensor that operates in a range of $-55^\circ C$ to $+125^\circ C$. It uses a 12-bit ADC to monitor and digitize the temperature to a resolution of 0.0625$^\circ C$, and have an accuracy of $\pm 1^\circ C$ maximum.

The communication between the ADT75 and the microcontroller is made by SMBus/I$^2$C (FIG 30). The output temperature can be formatted in 8 bits, 9 bits and 12 bits. The ADT75 I$^2$C bus can support an 8 sensors array.

5.3. HEAT RESISTORS

Due to the characteristics of the apparel, was chosen a flexible heater (FIG 31). The heater is a net made of nylon and a metal wire and it must cover the back palm. The heater uses a resistive wire that, when electrical current passes, will dissipate energy in the form heat. The dissipated heat by unit of length is enough to guarantee that surface of the wire does not reach a very high temperature, in order to not damage the fabric structure and burn the user skin.
5.3.1. Temperature control

The heat dissipated is controlled by a PID (Proportional, Integral and Derivative) controller algorithm. The PID uses the information from the temperature sensor to set the PWM value of the microcontroller, connected to a power MOSFET (FIG 32).

If the user undresses the mitt with the system turned ON, for a long period of time, there is the possibility of the heating element do not have enough power to make the process value reach the set point. When the user puts the hand inside the mitt the temperature will rise and will stay for a long period of time above the set point, until the sum of the negative error equals the positive ones. For that reason, the integral term of the PID controller must have a limit value.
Due the fact that the temperature is considered a slow variable, the PID sampling time is set to 200 ms, and that will reduce the time spend in the control process, making the system more efficient.

The workflow of the implemented algorithm can be seen in the FIG 33.

5.4. POWER MANAGEMENT MODULE

The power management module has the function of ensuring the power supply to all the other modules of the electronic control device (FIG 34).

For the commodity of the user the mitt includes a battery management chip. This chip will manage the charging voltage delivered to the batteries. The battery will be placed inside a pocket of difficult access, so an external power supply plug is needed for commodity.
The battery will deliver a voltage of 7.4\(V\) and, because the operational voltage of some components is 3.3\(V\), it was used a dc/dc converter, to low the voltage supply of this components.

![Diagram of battery management module]

**FIG 34** - Battery management module

### 5.4.1. Battery

From all the batteries technology available in the market, the Lithium Polymer batteries are the ones with the best performance regarding the requirements of the application.

The battery selected has a weight of 173\(g\) and can deliver a high amount of power. The batteries used in the mitt have 2 cells (7.4\(V\)) of Li-Pol batteries. They have a size of 134 \(\times\) 42 \(\times\) 13\(mm\) and they can deliver 3200\(mAh\).

If we consider that the consumption is made entirely by the heater (5\(W\)), the battery should last 4 hours and 15 minutes, when providing maximum heating power. However, the autonomy of the system is difficult to predict, because in one way the heater will not operate always on full power (favouring an higher autonomy), but in other way, at low temperatures, the internal resistance increases, diminishing the battery capacity, reducing the battery operation time.

### 5.4.2. Battery Management

The battery charger chosen was the Texas Instruments BQ24113A. This chip works autonomously from the microcontroller. The chip was designed to charge one or two cells of Lithium Polymer Battery packs. It has an automatic sleep mode for low power
consumption, a thermal shutdown for protection, a built-in battery detection, a maximum of $20\text{V}$ input voltage supply, and maximum charge current of $2.2\text{ A}$.

The thermal shutdown is controlled by the BQ24113A chip. It reads the temperature measurement of the battery using a thermistor placed in the battery. This thermistor is connected to a port in the battery management chip. The BQ24113A will shut down when temperature is higher than $45^\circ\text{C}$ and lower than $0^\circ\text{C}$, and it will maintained itself shutted down until the temperature gets in the charging temperature range.

If the battery charge is lower than a minimum value ($6\text{V}$ for two cells battery) (FIG 35), the BQ24113A will enter in a pre-charge mode. It will apply a pre-charged current during an interval of time (1800s). When the battery charge value is higher than $V_{\text{LOW}}$, after pre-charge time, the charger will enter in fast charge mode, otherwise it will send a fault warning.

FIG 35 - BQ24113A Typical charging profile\textsuperscript{(25)}
5.4.3. Solar panel

When designing an application for alpinism, Energy Harvesting technologies should be considered, because they provide a solution that can reduce the application weight.

The application developed is prepared to work with a flexible solar panel. However, that technology will not be implemented for now, due to several reasons: the flexible solar panels available in the market are not capable of deliver acceptable power values; the solar panel will be placed in a curve surface, reducing the overall efficiency; the solar panel it will not be always turned to sun, due to the constant movements of alpinist; the available flexible solar panels does not work at -30ºC.

5.4.4. DC/DC Converters

The components present in the developed circuit require two different operational tensions, one of 7.2V and another of 3.3V, for that reason it became necessary to include in the circuit a DC/DC converter (TPS62056). Its function is to low the higher tension (7.2V) to a 3.3V tension.

5.5. COMMUNICATION MODULE

![FIG 36 - Communication module](image)

5.5.1. Wireless Module

One of the requirements of this project was to use only one HMI to control the electronic system between the two mitts, in order to increase the usability of the system. Because of the hypoxia and the hypothermia, the alpinist needs a simple and
easy system to deal with. The solution found was to use wireless communication (Fig 36). To use wireless, were studded possible low power range technologies, like Wi-Fi®, ZigBee® and Bluetooth®. All this networks are viable solutions because they all have a suitable communication range, similar power consumption and small foot-print.

After analyzing the possibilities mentioned above, it was chosen the Microchip MRF24j40MA ZigBee® module (FIG 37). The main reason for the choice of this module was the microchip proprietary wireless protocol, MiWi™, which allows having less program memory in its wireless implementation. Less program memory implementation is important because the image storage, in the microcontroller, will consume much memory.

Microchip MRF24j40MA ZigBee® module uses a MRF24j40 chip that is a complete IEEE 802.15.4™ (ZigBee®) radio and operates in the 2.4GHz frequency band. It includes an antenna and all the components required to operate and manage internal tasks. This module has a low current consumption: Transmission 23mA; Reception 19mA; Sleep mode 2μA (26).

![Microchip MRF24J40MA Zigbee module](FIG 37 - Microchip MRF24J40MA Zigbee module (27))

5.5.1.1. MiWi™

MiWi™ is a Microchip’s proprietary wireless solution based on ZigBee® protocol stack. It is designed to help customers develop wireless applications and reduce programming time. The MiWi™ Development Environment (MiWi™ DE) package includes two Microchip’s proprietary protocols (MiWi™ Mesh and MiWi™ P2P). The MiWi™ DE is optimized for low-data rate and low-power. The MiWi™ protocol allows that less space is occupied in memory. The typical space memory are: 3-9kB for MiWi™ P2P; 2-17kB for MiWi™ Mesh and 40-96kB for ZigBee® (27).
MiWi™ DE mainly consists of two interface layers (FIG 38):

**MiApp** - Using the MiApp interface layer, the application developer can easily switch between different Microchip proprietary wireless protocols such as MiWi™ Mesh and MiWi™ P2P without having to change the application firmware.

**MiMAC** - Using MiMAC layer, the developer can easily switch between different RF transceivers such as MRF24J40 and MRF89XA.

The main advantages of MiWi™ DE are the easiness in developing wireless applications, the easiness in portability of the applications across different Microchip RF transceivers and different wireless protocols depending on the application requirements, without having to change the application firmware (FIG 39).
The major difference between the IEEE 802.15.4™ (Zigbee®) and the MiWi™ protocol is a less process needed to establish a connection. In the IEEE 802.15.4™ protocol for a peer-to-peer connection, the handshake is made by five steps (FIG 40): the device to connect sends a Beacon Signal Request; the devices capable of establishing a connection respond with a Beacon message; during a period of time, the first device receive the Beacon massages from all the peers and decide the one to establish the handshake process, and then sends a request command; after a predetermined time the first device sends a Data Request command and gets an Association Response from the other device (27).

FIG 40 - Typical Handshaking in IEEE 802.15.4™ (28)
In the MiWi™ P2P protocol is designed for simplicity, so the handshake process in the MiWi™ P2P Wireless Protocol is made in only two steps (FIG 41). The Device to Connect sends a P2P connection request command; any device in a rage capable of establishing a connection will respond with a command that finalizes the connection (27).

![Diagram](image)

**FIG 41 - Handshaking process for MiWi™ P2P wireless protocol**

A P2P MiWi™ requires that, in a point to point connection, one node act as a master and the other node as a slave. The master will find the channel with the least amount of noise and then send a connection request; the slave will search continually for a connection request in each channel. Each network has a number, defined by the programmer, that identifies the specific network, and only if the two nodes are configured in the same network it will be established a connection.

The master and the slave nodes use a different program memory. The master mode makes more complex operations, increasing the space for the software implementation.

The left mitt carries the HMI software using more PIC18F46J50 memory space (because of the images) so the master node will be placed in the right mitt. The parameters that will be transmitted are the battery state (no charger, charging, and charge complete); the percentage of battery left; and the right mitt interior temperature.

The terminate communication signal is also a synchronizing signal, this way the microcontroller can manage when the next connection will happen, and the MRF24j40 module can be awake from the sleep mode more efficiently. The implementation of the algorithm can be seen in the (FIG 42)
5.6. MICROCONTROLLER

The function of the microcontroller in the system is to measure, monitor, actuate and interact with all the peripherals components, according with a programmable logic.
For selecting the most suitable microcontroller for the Project were considered some factors: it must have all the number of ports needed (FIG 43) and the memory should have enough space to the images. The microcontroller selected was the PIC18F46J50. This PIC has two peripheral buses support, which can be used by a SPI or I2C connection; the clock can operate at 8Mhz; it has 64kb of programmable memory; a temperature range of $-40^\circ C$ to $85^\circ C$; low power consumption (6.2μA Typical and in sleep mode 105μA Typical); and 29 I/O pins, where 9 of those can be programmed as ADC, 4 as an external interrupt, and the other 4 as PWM output.

5.7. DEVELOPED ELECTRONIC DEVICE

The FIG 44 shows the electronic device that will be placed in the left mitt, where it can be quickly identified the HMI module, the flexible heater, the control temperature sensor (next to the flexible heater), the battery, the thermocouple sensor, and the exterior temperature sensor. In the FIG 45 all elements are similar, except the exterior temperature sensor and the HMI module, which are not present in the right mitt.
6. DESIGN CONSIDERATIONS

After the choice of the most suitable materials for the construction of the mitt, they will be arranged as shown in the FIG 46.

In the three first layers the material covers the full area of the mitt, because their function is to insulate. Between the layers 2 and 3 a matt of Thermal Wrap is placed in the palm area, reducing the thickness of the mitt. Between layers 3 and 4 is placed the flexible heater, that way it never touch the skin, reaching higher temperatures without burning the user. The fourth layer covers the hand and wrist area, that way the hot air that comes from the heater will flow easily thru the hand. In layer 5 the Coolmax® fabric will be extended almost to the end of the mitt, making some of the excessive water be expelled.

FIG 46 - Mitt Layers Design Structure
In a mitt the only finger available to operate the keyboard efficiently is the thumb, and for that reason, the best place for putting the HMI interface is in the inner part of the arm (FIG 47a). The HMI being placed in that location will force the user to turn his hand up, making the radius and the ulna bone be in flat position, an ideal position to operate the keyboard with the right thumb. That way the keyboard will have a larger area to stand, dispersing the pressure trough the fabric immediately below, making less flatness in the insulation and allowing that the button has the needed support for the pressing operation, giving a better experience to the user.

In the wrist area will be incorporated a nylon strap. This strap has the purpose to thigh the mitt to the arm to prevent the mitt from falling. The strap must have in the end a thicker part (FIG 47b), for user pull it with his teeth to adjust the tightness.

![FIG 47 - (a) HMI placement; (b) wrist nylon strap for adjustment](image)

Using tools while wearing the mitt is difficult, due to the cushioning volume and the reduced friction between the fabrics. Dress them is a challenge for the same reasons. The solution found was to place a nylon strap in the mitt opening (FIG 48) so the user can place the thumb and push the mitt to its right place. Other function for this strap is that the user can hang the mitts in his waist or backpack while he is not wearing them.
The battery should be placed in the lower part of the mitt (Fig 49), inside a pocket, next to the wrist nylon strap in order to prevent displacement of the battery. The pocket must be made of a insulated material to protect the battery from the cold, increasing that way the effective battery capacity.
In the back palm of the hand there will be a square of soft fabric, for the user scratch his nose and to remove the ice from the face (FIG 50)

FIG 50 - Mitt back with square of soft fabric
7. TESTS AND VALIDATION

Although there is a rigorous testing protocol, the process of programming this kind of application evolves a constant testing. The microcontroller is programmed by stages, i.e., when everything is working correctly the next stage is initiated, this way, if there is a problem it is easier to identify where it occurs. The quality management states that when all the system is implemented all testing protocols procedures must be verified one by one, even those that were verified in the programming phase, reducing the error probability.

After the mitt prototype is completed it must to be submitted to physical and thermal analysis with a sweating thermal manikin with physiological control model in controlled environment. The results of those tests will tell us if the mitt have the predicted behaviour. For tuning the PID controller the mitt should be placed inside a refrigerated environment, and then the required tests should be performed, in order to determine the best proportional, integrative and derivative gains. In this stage will be possible to make a first analysis of the power required to the battery.

For tuning the PID controller the mitt should be placed inside a refrigerated environment, and then the required tests should be performed, in order to determine the best proportional, integrative and derivative gains.

After an expedition to a mountain higher than 8000 meters, the charge level of the batteries must be analyzed in order to know if the power is adequate to the requirements, because a high level of battery will mean that the weight carried could be reduced.
8. CONCLUSION

Alpinism garment is not foreseen for mass market, because the number of practitioners is low, comparing to other sports. Due to that fact the scientific development of specific equipment for alpinism is reduced. In general the Alpinism equipment is improvised, adapted solutions from other activities that do not fulfil the real needs.

With this work was possible to conclude that is not easy to predict the real functioning of the mitt application. The unpredictability of the human body behaviour in a harsh environment, such as the high-mountain environment, makes it very difficult to establish an exact value of all parameters.

The mitt solution (apparel + electronic control system) was designed based on scientific data. Theoretically, the result will work properly in a Alpinism expedition, but in practice there is no enough information, because the validation tests were not performed yet.
9. FUTURE WORK

Technology is always evolving and some of the best solutions available today have not reached their entire potential or are yet too costly.

In this project, we identified some points that in the future can be changed or added, in order to improve the overall efficiency of the system.

With the increase of investigation related with batteries and solar panel technologies, in the future, these elements can be changed or implemented in order to reduce the overall weight.

Other possible modification is the change of the LCD display to an electronic paper display. The electronic paper display spends a very low amount of energy, allowing the information be always available on screen and they can be easily read under intense sunlight. In this moment, it is not possible to implement this kind of display, for 3 reasons: they are not easy to acquire; the price is much higher than the regular LCD; and they do not work in the required temperature range.

The usage of a flexible far infrared heater (FIR) must be considered in a next version of STA. This type of heaters presents very interesting characteristics: they distribute the heat in a more efficient way and if suffers damage it continues operating, because its structure is not a continuous wire like the used in STA 1.

It would be interesting to incorporate a memory to store data of all the temperature values, as well as the set point values and the battery state, in order to study the system behaviour and optimize it.
ACRONYMS

A₅ – Plane surface area

ATP - adenosine triphosphate

Bpm – Beats per minute

Clo – Clothing insulation value

D_{output} – Derivative controller

E – Error

E_{diff} – Heat loss due to vapour diffusion through the skin

E_{resp} – Heat loss respiration latent heat loss

E_{rs} – Heat loss due to evaporation of regulatory sweating from the skin

HMI – Human machine interface

h_{conv} – Convection heat transfer coefficient

h_{rad} – Radiation heat transfer coefficient

I_{output} – Integrative controller

k – Thermal conduction coefficient

K_d – Derivative gain

K_i – Integral gain

K_p – Proportional gain

L – Sensible (dry) heat loss, respiration

M – PID controller output

PID – Proportional, integrator and derivative controller

PV – Process output value

P_{output} – Proportional controller
$P_s$ – Saturation vapour pressure

$P_v$ – Partial vapour pressure

$P_w$ – vapour pressure

$\dot{Q}$ – Rate of heat transfer

$\dot{Q}_{\text{cond}}$ – Conduction heat transfer

$\dot{Q}_{\text{conv}}$ – Convection heat transfer

$\dot{Q}_{\text{rad}}$ – Radiation heat transfer

RH – Relative humidity

SP – Set point

STA1 – Space Technologies on Alpinism Phase1

$T_d$ – Dew point

U – Relative humidity

$\alpha$ – Absorptivity

$\varepsilon$ – Emissivity

$\sigma$ – Stefan-Boltzmann constant

$\eta$ – Efficiency
GLOSSARY

A

**Alpinism** – sport or activity of climbing of the Alps or any equally high mountain ranges.

**Amino acid** – a simple organic compound, containing carboxyl (−COOH) and an amino (−NH₂) group.

**Anabolism** - the synthesis of complex molecules in living organisms from simpler ones together with the storage of energy; constructive metabolism.

**Anemia** - a condition marked by a deficiency of red blood cells or of hemoglobin in the blood, resulting in pallor and weariness.

**Apathy** - lack of interest, enthusiasm, or concern.

**Arrhythmia** – one or more irregularities in the force or rhythm of the heartbeat.

**Arterial blood pressure** - blood pressure in the arterial walls during the cardiac contraction.

**ATP** - adenosine triphosphate; a compound consisting of an adenosine molecule bonded to three phosphate groups, present in all living tissue. The breakage of one phosphate linkage (to form adenosine diphosphate, ADP) provides energy for physiological processes such as muscular contraction.

B

**Basal metabolism** - rate at which the body uses energy while at rest to keep vital functions going, such as breathing and keeping warm.

**Bradycardia** – abnormally low cardiac frequency (less than 60 bpm).
C

**Cardiac Frequency** - Number of times that heart contracts in a minute.

**Cardiac output** - is the volume of blood being pumped by the heart, in particular by a left or right ventricle in the time interval of one minute.

**Catabolism** - the breakdown of complex molecules in living organisms to form simpler ones, together with the release of energy; destructive metabolism.

**Cellular metabolism** – also known as cellular respiration; set of the metabolic reactions and processes that take place in the cells of organisms to convert biochemical energy from nutrients into adenosine triphosphate (ATP), and then release waste products.

**Coma** - state of deep unconsciousness that lasts for a prolonged or indefinite period, caused especially by severe injury or illness.

**Condensation** - process by which a gas is converted from vapour form to its liquid form.

**Conduction** – interaction between particles with different energy, where the more energetic transfers energy to the less energetic.

**Convection** - heat transfer from a solid surface to a liquid or gas, in motion.

**Core temperature (human body)** - temperature of the deep structures of the human body, in comparison to the peripheral tissues temperature.

**Cyanosis** - a bluish discoloration of the skin resulting from poor circulation or inadequate oxygenation of the blood.

D

**Dehydration** – excessive loss of body water.

**Delirium** - an acutely disturbed state of mind that occurs in fever, intoxication, and other disorders and is characterized by restlessness, illusions, and incoherence of thought and speech.

**Dyspnea** – a difficult or labored breathing.
**E**

**Erythropoietin** - a hormone secreted by the kidneys that increases the rate of production of red blood cells in response to falling levels of oxygen in the tissues.

**Euphoria** - a feeling or state of intense excitement and happiness.

**Evaporation** - process by which water is converted from its liquid form to its vapor form.

---

**F**

**Fatty acids** - a carboxylic acid consisting of a hydrocarbon chain and a terminal carboxyl group, esp. any of those occurring as esters in fats and oils.

**Frostbite** - injury to body tissues caused by exposure to extreme cold, typically affecting the nose, fingers, or toes and sometimes resulting in gangrene.

**Frostnip** - the first stage of frostbite.

---

**G**

**Gangrene** – a localized death and decomposition of body tissue, resulting from either obstructed circulation or bacterial infection.

---

**H**

**Hematologic components** – the elements that compose the blood: leukocytes, red blood cells and platelets.

**Hemoglobin** - a red protein responsible for transporting oxygen in the blood of vertebrates. Its molecule comprises four subunits, each containing an iron atom bound to a *heme* group.

**High-Mountain** – mountain above 2500 meters of altitude.
Homeostasis - the tendency toward a relatively stable equilibrium between interdependent elements, especially as maintained by physiological processes.

Hypertension – abnormally high blood pressure, when the systolic pressure, of a rested person, is $\geq 140\ mmHg$, and diastolic pressure is $\leq 90\ mmHg$.

Hypobraric - relating to conditions of low air pressure and low oxygen content, such as atmospheric conditions at high altitudes, or in special chambers used to establish low-pressure conditions.

Hypoglycemia – deficient amount of glucose in the bloodstream (Adult glycemia $\leq 70\ g/dl$).

Hypothalamus – a region of the forebrain below the thalamus that coordinates both the autonomic nervous system and the activity of the pituitary, controlling body temperature, thirst, hunger, and other homeostatic systems, and involved in sleep and emotional activity.

Hypothermia - condition of having an abnormally low body temperature, typically one that is dangerously low.

Hypoxia – presence low amount of oxygen in the tissues.

L

Lethargy – condition of lack of energy and enthusiasm, which cannot be overcome by the will.

Lipids - any of a class of organic compounds that are fatty acids or their derivatives and are insoluble in water but soluble in organic solvents. They include many natural oils, waxes, and steroids.

M

Metabolism - chemical processes that occur within a living organism in order to maintain life.

Metabolite - a substance formed in or necessary for metabolism.
**Monosaccharide** - any of the class of sugars (e.g., glucose) that cannot be hydrolyzed to give a simpler sugar.

**Mountaineering** - sport or activity of climbing mountains.

**N**

**Nausea** - a feeling of sickness with an inclination to vomit.

**Nucleic acid** - a complex organic substance present in living cells, especially in DNA or RNA, whose molecules consist of many nucleotides linked in a long chain.

**Nutrients** - a substance that provides nourishment essential for growth and the maintenance of life.

**O**

**Osmosis** - process by which molecules of a solvent tend to pass through a semipermeable membrane from a less concentrated solution into a more concentrated one, equaling the concentration on each side of the membrane.

**Oxygenation** – process of supplying, treat, charge, or enrich with oxygen.

**P**

**Partial pressure of inspired oxygen** (PIO\(_2\)) - pressure of O\(_2\) calculated at sea level. At sea level, the atmospheric pressure is 760 mm Hg. This equals the force exerted by a column of mercury 760 mm high. Since the atmosphere is 21% oxygen, the partial pressure of O\(_2\) is 0.21 x 760 = 160 mm Hg.

**Polysaccharide** - a carbohydrate (e.g., starch, cellulose, or glycogen) whose molecules consist of a number of sugar molecules bonded together.

**Pulmonary alveolus** - small polyhedral outpunchings along the walls of the alveolar sacs, alveolar ducts and terminal bronchioles through the walls of which gas exchange between alveolar air and pulmonary capillary blood takes place.
R

**Radiation** - energy emitted by a body in the form of electromagnetic waves, at a determined temperature.

**Raynaud’s Syndrome** – Spasmodic contraction of the peripheral blood vessels, mainly fingers, showed by the cold and pail hands, prone to ulcers and gangrene by poor circulation.

**Relative humidity** - the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature.

S

**Seizure** - Uncontrolled electrical activity in the brain, which may produce a physical convulsion, minor physical signs, thought disturbances, or a combination of symptoms.

**Stupor** – a state of near-unconsciousness or insensibility.

**Synthesis** – the production of chemical compounds by reaction from simpler materials.

T

**Tachycardia** – abnormally high cardiac frequency (more than 100 bpm).

**Tachypnea** - abnormally rapid superficial breathing; reflex response to the stimulation by the vagus nerve in the pulmonary vessels.

**Terminal burrowing behavior** - autonomous process of the brain stem, which triggers a behavior pattern observed in the last stages of lethal hypothermia, producing a primitive and burrowing-like behaviour of protection, as seen in hibernating animals, where people tend to hide themselves under a bed, behind a wardrobe, in a shelf etc.

**Thin air** – air with low amounts of oxygen saturation.

**Throbbing** – a feeling of pain in a series of regular beats.
V

**Vapor pressure** – the pressure of a vapor in contact with a liquid or solid form.

**Vasoconstriction** - constriction of blood vessels, which increases blood pressure.

**Ventricular fibrillation** – sudden and rapid contractions of the heart ventricles, leading to a circulatory arrest, which quickly becomes lethal.

**Visual Impairment** - low vision is a severe reduction in vision that cannot be corrected with standard glasses or contact lenses and reduces a person’s ability to function at certain or all tasks.
REFERENCES


## ANNEX A – Efficiency and Metabolic Rate for typical tasks

<table>
<thead>
<tr>
<th>Type of Activity</th>
<th>Metabolic Rate Per Unit Body Surface Area</th>
<th>Estimated Mechanical Efficiency</th>
<th>η</th>
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<tr>
<td></td>
<td>kcal/m²/hr</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>Seated, quiet</td>
<td>50</td>
<td>58</td>
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<tr>
<td>Seated, drafting</td>
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<tr>
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<td>0-0.10</td>
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<tr>
<td>Sweeping a bare floor</td>
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<td>mason work</td>
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</tr>
<tr>
<td>m/s</td>
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<td>Velocity m/s</td>
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