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DEVELOPMENT OF A PORTABLE ROBOTIC ARM FOR A DEMINING ROBOT

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Development of a portable robotic arm for a demining robot

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Desenvolvimento de um braço robótico para robô móvel de remoção de minas

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Abstract

In this dissertation, a new portable 4 degrees of freedom robotic arm was developed for humanitarian purposes. The arm, although to be mainly used on an existing skid-steered wheeled robot platform, has a flexible design and it can be easily mounted on other robots with different frames, by changing the base plate. The proposed arm consists of a wire-driven system, keeping the motors away from the metal detector, hence distorting demining operations least. This dissertation, also discusses the robotic arm currently in use, and lists its limitations along the implementations made to improve some of the mechanisms like adding compliance

The major challenges in building a robotic demining arm is adding compliance and keeping the arm metal free. Compliance helps to protect the arm from any harm due to collisions with obstacles or the surface. Metal, when close to the metal detector, interferes with its functioning, reducing its sensitivity, and even making it blind to landmines. Therefore the mechanisms have to be flexible and the joints close to the metal detector should not have metals attached or surrounding them. It is important for the metal detector carrying arm to have more than two controllable DoFs, especially if it is going to be used on non-flat terrains.

The new arm will be completely assembled and tested in the near future and is estimated to weight 45% of the existing arm, weighting approximately 9 kg. This is drastic decrease in weight and it will boost the energy efficiency of the robot, extending its battery life as well as decreasing wear. Further improvements to the weight are still possible, and these could be achieved by optimizing the material used in the sheets and other components.

Keywords Demining, Robot, Robotic arm, Wire-driven mechanism, Micro servo motor

RESUMO

Nesta dissertação, um novo braço robótico móvel de 4 graus de liberdade foi desenvolvido para fins humanitários. O braço, embora seja usado principalmente numa plataforma de robô com rodas antiderrapantes, o design é flexível e pode ser facilmente montado em outros robôs com molduras diferentes, mudando apenas placa de base se necessário. O braço proposto consiste em um sistema acionado por fios, mantendo os motores afastados do detetor de metais e, portanto, diminuindo o erro das leituras. Esta dissertação, também discute o braço robótico atualmente em uso e lista as suas limitações.

Os principais desafios na construção de um braço robótico de remoção de minas é a sua compliance, capacidade de colidir com um obstáculo e manter flexibilidade para não danificar nenhum componente, e a capacidade de controlar os graus de liberdade no detetor de metais sem ter componentes metálicas perto do detetor. A importância de ter mais do que dois DoFs controláveis foi considerada crucial nos robôs de remoção de minas para terrenos não regulares, portanto, esforços futuros devem ser feitos para implementar mecanismos similares ao apresentado neste trabalho em todos os robôs de remoção de minas.

O braço robótico será completamente montado e testado num futuro próximo. A redução de peso estimada é de 55%, pesando agora aproximadamente 9 kg. O que é drástico e aumentará a eficiência do Husky. Mais investimentos poderiam ser feitos para reduzir o peso ainda mais, como otimizar o material utilizado nas chapas. Depois de construir e testar o braço, de acordo com os resultados, poderia ser estudado a necessidade de implementar o 5º grau de liberdade no detetor de metais, o que implicaria uma nova junta de esfera no detetor de metais e um novo sistema de fio conduzido. Além disso, ainda há espaço para melhorar a qualidade de alguns dos componentes do braço, como as juntas e os elos de plástico.

Keywords Acionamento por fios, Robô, Desminagem, Braço robótico, Micro servo motores

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ACRONYMS

3D – Three-Dimensional

ABS – Acrylonitrile-Butadiene Styrene

DoF – Degree of Freedom

IRS-UC – Institute of Robotics and Systems of University of Coimbra

DEM – Departamento de Engenharia Mecânica

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

MIT – Massachusetts Institute of Technology

1. INTRODUCTION

The wide use of landmines has created a global humanitarian and ecological crisis. The lands contaminated by landmine could be farmed, used for transportation, or inhabited making them socially and economically valuable. However, the landmines deny any of these options. An example of this, was in 1996, when the Norwegian Peoples Aid cleared a village in Mozambique after all the civilians had abandoned it due to an alleged mine infestation. After the demining of the village, there were found only four mines. Four mines were responsible for denying access to around 10000 people to their homes and land.

In Cambodia along with Malaria and Tuberculosis, landmines have ranked as one of the three most severe public health threats. In Afghanistan, landmines have claimed 20-25 victims a day for years. These figures are common in many countries contaminated by landmines. It is estimated that over 100 million landmines are buried in 64 countries and another 100 million are stockpiled ready for use.

Despite the enormous effort we have witnessed in the development of new ways to perform demining using various means ranging from using animals to using autonomous robots, the number of truly successful applications is still low. Amongst other factors, the main reason for this can be explained by the limitations in cost. Most of the affected countries are poor and cannot heavily invest in solutions, hence the advancement of demining applications is not as fast as it could be, especially in robotic demining which requires high initial investment.

The motivation behind this work is to propose an affordable mechanical system for the mechanical demining arms that are to come in the future, providing a base foundation for the use of wire driven mechanisms along with other implementations made in this new developed arm.

This work is divided into 4 chapters, starting by an introduction, motivation and goals of this research. The second chapter is the state of the art of main topics of this research, namely demining robots arms and wire driven systems. The third chapter is the presentation of the implementations of the new arm. At last, in the fourth chapter, the conclusion and the future work of this research are presented.

This rest of this chapter, which started by providing an introduction to the problem of landmines and a possible solution for demining, is organized as follows. The landmines problem is described in section 1.1. Section 1.2 is dedicated to the motivation behind humanitarian demining. The solutions currently used for humanitarian demining are discussed in section 1.3 and 1.4. Finally, the goals of this research work are formulated in section 1.5.

1.1. Landmines

In military science, minefields are considered a defensive or harassing weapon, used to slow the enemy down, to help deny certain terrain, to direct enemy into a kill zone or to reduce morale by randomly attacking material or personnel [1]. Unfortunately the landmines last much longer than the conflict, post conflict landmines related casualties are exclusively civilian.

Landmines are composed of mainly plastic and metal. They contain explosives and sometimes pieces of metal or other objects meant to cause additional injury. The explosives have sensitive detonating systems which can be triggered by pressure, movement, sound, magnetism or vibration.

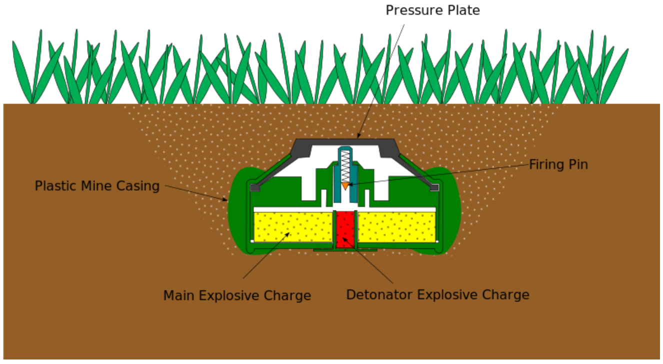

Figure 1.1 – Anti-Personnel Landmine components, Blast type [1].

Landmines have been divided into anti-personnel and anti-tank mine. Anti-tank mines are built with the purpose of destroying vehicles. Hence, they are triggered by high pressure only. During World War II, anti-tank mines accounted for half of all vehicles disabled [1]. Anti-personnel mines are designed to kill or injure soldiers. They are a small explosive devices designed to be detonated by pressure, radio signal, other remote firing methods or the proximity of a person. As no one controls the detonation of landmines, they can claim any victim and kill or injure anyone.

Figure 1.2 - Sand-colored VS-50 mine intended for use in desert environments (shown beside a wristwatch, for scale) (Left) and Italian Valmara 69 bounding type anti-personnel mine (Right).

Anti-personnel mines costs between \$3 to \$30 each and clearing them can cost from \$300 to \$1000 per mine. Even with professional deminers, it is estimated that for every 5000 mines extracted, one individual dies and two are injured by accidental explosions.

1.2. Motivation for humanitarian demining

Landmines are a problem in many countries, from South America to Asia. While some countries are ratifying or acceding to the Mine Ban Treaty, the major producers of antipersonnel landmines, which are USA, Russia and China are still to take part in this treaty along with 13 other countries [2].

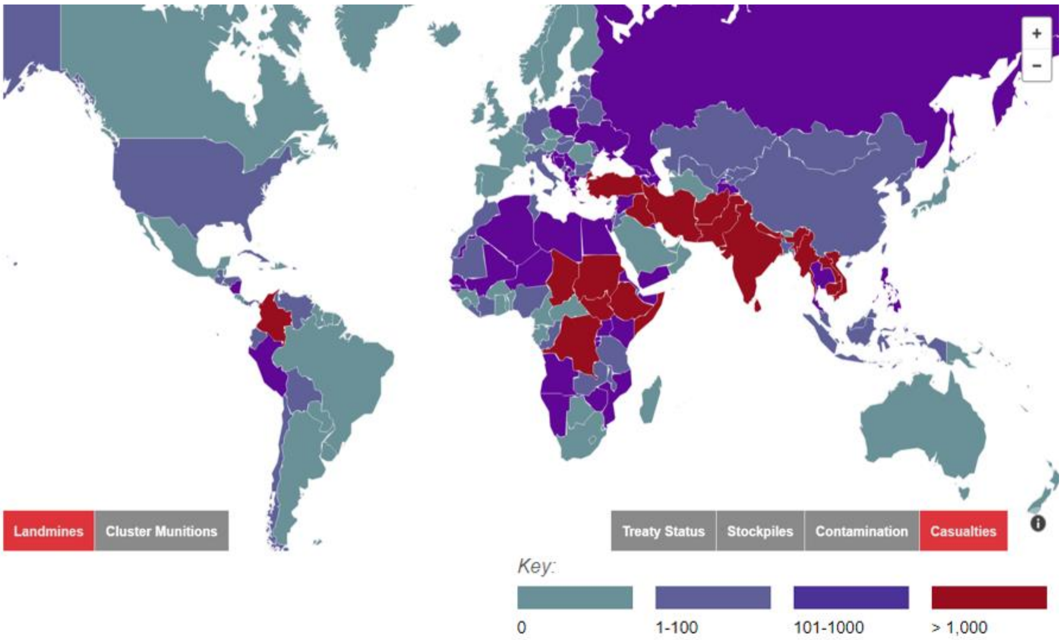

Figure 1.3 - Global Landmine casualties [3].

The International Campaign to Ban Landmines maintains a comprehensive report about the world landmine problem. The interactive map given in Figure 1.3, is from the *Landmine Monitor* which is published every year and presents an update of the situation in the countries with landmine problems, based on treaty status, stockpiles, contamination and casualties along with other information. According to the interactive map shown on Figure 1.3 there are 20 countries that have had casualties above 1000 in the last 16 years, with Afghanistan leading with more than 20000 casualties followed by Colombia and Cambodia with 10000 and 8000 respectively.

Most of nowadays casualties and damage are due to the landmines buried back in the years of conflict. When the Soviet Union went to war with the Mujahideen freedom fighters in 1979, they mined in a completely indiscriminate manner, with no regards for civilian casualties, from schools, grazing fields to waterways all across the country until 1989, when the war ended. Later in 2001, the USA invasion began and this worsened the situation. It is believed that there are currently 10 million mines spread across the impoverish country mainly from the times of the Soviet invasion. The most infamous mine of that occupation period was the “Butterfly” mine, which is covered in green plastic and is mistaken by many children for a toy. It is not known how many of these mines exits, but it is believed that they were dropped by helicopter crews in millions. In Afghanistan, landmines claim between 20-25 victims a day. Of these 8000 victims annually 4000 survive. At an estimated cost of 5000 dollars per victim for rehabilitation, the direct cost for survivors of landmines incidents in that country alone is $20 million annually [4].

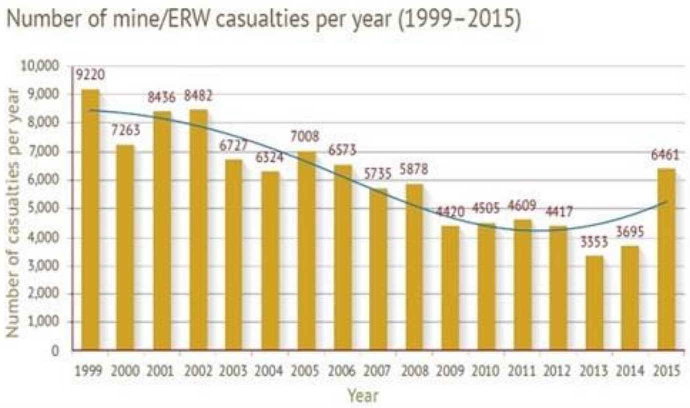

Figure 1.4 – Number of mine casualties per year (1999-2015), showing sharp increase in the past years [5].

According to the International Committee of the Red Cross, war surgeons classified the landmine injuries as the worst to be treated. On stepping on an anti-personnel mine, the blast can often tear off a person’s foot or leg. Sometimes the explosion is strong enough to kill a person immediately, if not, it is always necessary to amputate.

There are three types of anti-personnel land mines; blast, fragmentation and bounding fragmentation. Blast landmines typical create a blast explosion from detonation, whereas fragmentation mines besides the blast also throw metal fragments. The bounding fragmentation mines jump to waist height before exploding, hence they are more devastating. These mines usually have a wire attached to them and they contain hundreds of steel balls to increase the potential damage. If someone walks into the wire, the mine explodes and then the steel balls are scattered in a large area, damaging possibly more than one person.

Mines can explode and injure any person; an innocent civilian passing by and slightly touching the mine, a curious kid accidentally discovering and trying to play with it, a farmer planting rice in Cambodia, a trained personal removing the mine, or even the person laying it.

Figure 1.5 - Planting rice in Cambodia [6] (Left) and Children in Cambodia playing near a landmine field (Right) [7].

Landmines are also unpredictable. In 1977, Somalia and Ethiopia were at war and the mountains near the town were mined. Fifteen years later, after heavy rain, strong winds, snow, the soil was washed away and the small plastic mines ended up on the shore claiming a victim [8].

Mines are mainly laid on the countryside, where the nearest hospital can be hundreds of kilometers away and there is often little transportation. Therefore it may take as long as two weeks for an injured person to arrive at a hospital and receive medical help. It is estimated that half of the people who are injured by mines ever get to a hospital, while the others die, sometimes slowly and painfully, from infections or loss of blood.

The treatment is also very difficult. Those who are lucky to get to a hospital have usually lost a large amount of blood and their wounds are infected combined with dirt in the wounds which makes the surgery necessary to amputate the limb very difficult, requiring more than one operations. Many doctors from “developed” countries, do not have the experience and training to take care of these patients, committing mistakes and possibly leaving the patient with problems after the operation, for example by not removing all the dirt. Children are considered the worst victims not only because they are young and naive but because their bones grow faster than their flesh and muscles. Therefore as the child grows, the bone may come out of the skin and then the limb has to be amputated again. Also, because children soon grow too big for their artificial limbs. If they do not get new ones quickly, they can have problems with their hips and spines.

Thus, the victims commonly suffer permanent disability, require multiple operations, multiple amputations and extensive rehabilitation, which have social, psychological and economic consequences. The damage does not end there, the destruction caused by the landmine makes the land dry, the soil less fertile and it might leak chemical components which could poison the water and soil.

Analysis of the contribution of landmines to land degradation was conducted at University of California, Berkeley, USA. It has been stated that movement of topsoil, introduction of harmful heavy metals, rise in salt contents, decrease in organic matter content and soil crusting necessarily contribute towards land degradation [9]. This has been broadly summarized in figure 1.6.

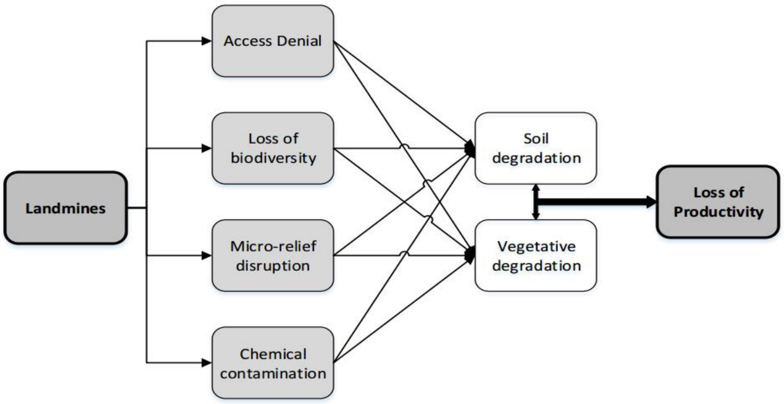

Figure 1.6 – Compounding of landmine effects to result in loss of productivity and associated socio-politico-ecological problems [9].

Landmines have restricted agricultural production on a large scale. In 2000, it was reported that in the absence of landmines in Afghanistan the productivity there could have increased by 88–200 per cent compared to pre-war levels. It is estimated that these lands would have been enough to feed 16 million people annually.

Land degradation leads to many complex socio-political and economic problems, including but not limited to, exploitation of available resources beyond their ecological carrying capacity, unemployment, poverty, social marginalization, desperation, and aid dependency.

The root problem is the landmines staying in the ground peacefully and being a hindrance for normal activity. According to the data available, there are more than 110 million mines scattered in more than 70 countries (around one mine per 50 inhabitants of the planet). Experts believe that at the current demining pace, it would take more than 1000 years to remove all the mines in the world, assuming no addition of landmines.

Figure 1.7 - Argentinian minefield at Port William, Falkland Islands created in 1982; clearance inhibited by boggy terrain (Left) and Syrian minefield on the Golan Heights more than 40 years old (Right) [1].

1.3. Types of mine clearance

Demining is a process involving surveys, mapping and minefield marking, and mines actual de-activation and removal from the ground. Mine clearance can be divided into two, humanitarian and military.

The military process, known as breaching, just clears the soldiers' strategic pathways, whereas humanitarian mine clearance is a social cause to restore peace and security at a community level. Humanitarian demining seeks to restore the land to the people, clear areas for public safety, so the civilians can use these areas without any fear or anxiety of explosives. Unfortunately this clearance is not only time consuming but the money involved in these clearances is much higher, amongst other factors the main reason is that in the current demining processes, there is still the need of having professionals and there are still many false alarms, hence if the process is too slow and time consuming, then more money will be spent on those services.

Figure 1.8 - Iraqi land mines laid on the road (Left) and on the field (Right) to stop US army advances [10].

Minefields are located in very different environmental conditions and landmines can have different types, shapes, sizes and materials which complicated the development of a standard detection method.

There are three main methods for mine clearance; manual technique, animals and mechanical demining.

1.3.1. Manual demining

The manual technique being the only effective manner to remove and destroy a landmine. The manual technique is basic but tedious and dangerous, requiring good skill of the deminer. The deminer probes the soil in front of himself centimetre by centimetre using a prober until discovering an object by the force which the prober returns to the deminer's hand. Normally demining is done by the use of a handheld contactless mine detector which sweeps over the ground. Since landmines usually contain some amount of metal, they are expected to be detected with a metal detector. However some landmines include only some grams of metal (a fuse) which makes them undistinguishable from metal debris left in the ground. The small amount of metal makes their detection more difficult, and mines can always be confused with metal debris, due to this there exist a lot of false alarms in this process and every alarm has to be carefully evaluated. It's observed that only one metal detector alarm in every one thousand is a mine. Moreover, there is always a chance of human mistake or equipment malfunction resulting in loss of lives and in this case a professional deminer.

Figure 1.9 - U.S. Army Technician deactivating a landmine in Fallujah, Iraq [1] and HALO Trust Afghan manual deminer in Ghandaki Village, Afghanistan [11].

1.3.2. Animal demining

The purpose of using animals for demining is to locate the landmines and it relies on the animal's olfaction senses to detect the explosive vapours leaking from landmines. They are much better than any man-made detector and animals do not respond to non-explosive objects which eliminates the short comings of manual detection techniques. The animals currently used are dogs or African-pouched rats. There are a few drawbacks to this method, such as the very high cost of training dogs or rats. Also the animals can be overwhelmed in areas of high contamination, become confused, can only work for a couple of hours and their effectiveness completely depends on their level of training and skill of handlers.

Figure 1.10 - Mine detection dogs and their trainers in Kandahar, Afghanistan [12].

In the past years there has been research carried out using rodents and this research has proved rodents can be the cheapest form of landmine detector. Better sense of smell, cheap, easy maintenance, transportation, resistance to tropical disease and light enough to cross terrain without triggering explosives, are some advantages of using rats. Using rats is a very common practice in Mozambique by Belgian non-governmental organisation Apopo [13].

Figure 1.11 - Apopo-trained rats and their trainers in Mozambique.

1.3.3. Mechanical demining

The last method is mechanical clearance and it is most common in the military. Where armed vehicles are run through the land to activate the mines. In the case of personnel landmines the explosive force is not enough sufficient to damage the vehicle, however this method has still many drawbacks despite the existence of many commercial vehicles on the market. These vehicles are terrain specific, expensive and not 100% reliable. They can end up burying the mines deeper or partially damaging them and even moving them to the side, leaving them more vulnerable to explode. Usage of these heavy vehicles brings logistical problems associated with transportation to remote areas in countries with little infrastructure, also the manoeuvrability of wheeled vehicles is challenging, requiring flat terrain and tracked wheels, unable to climb steep terrains. Despites all these drawbacks, this methods along with manual efforts smooths the procedure of mine removal by saving time and making it safer for deminers to do their job.

Figure 1.12 – A US Army Panther mine clearing tank fitted with mine rollers [14] (Left) and MIneWolf mine clearance machine [15] (Right).

1.4. Demining Robots

In order to eliminate the threat of landmines cost is going to be a factor. The past 20 years have been dedicated to finding solutions that could speed and automate the demining process by replacing the deminers in these dangerous conditions, especially in the robotic field. There have been great advances in technology which have allowed creating robots that could aid in the removal of landmines without risking personal or material damage.

Suppose having a mobile robot and a detector attached to it, the effectiveness should be similar to manual detecting. Adapting this to a portable platform, should help improve the safety of personnel along with efficiency, productivity and flexibility. In the design and development of a reliable demining robot, new challenges arise in a wide variety of fields. These include robotic mechanics and mobility, sensor and sensor fusion, autonomous or semi-autonomous navigation, and machine intelligence.

Many humanitarian projects around the world are trying to put resources towards reliable robot platforms for demining. There are efforts on ground vehicles and air borne robots which can be tele-operated, as well as platforms that are semi-autonomous or autonomous and can carry out operations of navigation, mine detection and mapping and its removal or neutralization.

Demining cannot be carried out if locations of individual mines are unknown. Thus, mine detection, and in general, mine sensing technologies are of major importance and currently a slow process in demining. The purpose of researchers today is to reach greater efficiency in detection, in order to speed up the detection rate, reliability, accuracy and efficient distinguishing between explosives and other buried debris ensuring more safety of the deminers and the environment. Most of nowadays demining robots are in the testing phase, being transported to actual minefields and being tested on practice landmines in order to help benchmark performance of their equipment, systems and the algorithms leading to enhancements.

These researches also face hindrance like designing of a universal robot for different terrains or different environmental conditions along with quality trained technicians to use the robot of high cost and sophisticated technology. If proven to be reliable then these can have mine removal equipment which eliminates the need for in person removal of mines.

1.5. Goals for this research work

The Institute of Systems and Robotics of University of Coimbra (ISR-UC) took part in a European project called Tiramisu whose main objective was to provide a toolbox to aid in humanitarian demining. The ISR-UC team's contribution was a mobile autonomous ground robot capable of understanding the characteristics of the terrain and navigating it in addition to detecting mines and creating a map of their locations.

The ISR-UC team is always working on ways to improve the robot performance, more specifically in this case the capability of mine sweeping on non-regular terrain. In that context, this dissertation main goal is to design and develop a new customized portable robotic arm to solve the problems and limitations of the current arm.

The main drawbacks of the existing arm are its heavy weight and allowing real time control of only two of the four Degrees of Freedom (DoF) available. Furthermore since it is a completely new design it makes sense to analyse all the other limitations and problems of the arm and propose solutions to correct and improve them.

The current arm and the topics which will be addressed and improved in this project can be seen in the following pictures:

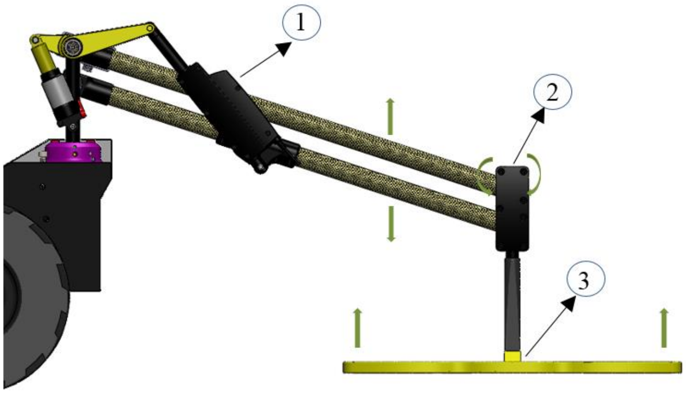

Figure 1.13 – Improving points, in green the illustration of the DoFs.

1- The current pitch mechanism is heavy, slow and creates vibrations.
2- Control the yaw DOF.
3- Control the roll DOF.

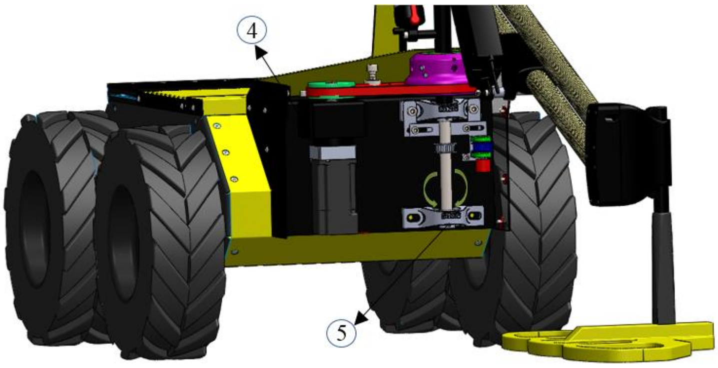

Figure 1.14 – The other improving points, in green the illustration of the DoFs.

4- Existing connecting sheet is over dimensioned, weighting 7 kilograms.
5- Sweeping mechanism is too heavy.

2. STATE-OF-THE-ART

2.1. Demining robots

One of the most urgently needed applications for mobile robots is demining. Using robots in a minefield is accomplished with severe demands for mobility and adaptability in a rough environment that could be, covered with dense vegetation, hot and dusty making it impossible to use traditional electronics meant for indoors, along with other complications involved. This state-of-the-art on demining robots aims to review some well-known demining robots that have been developed.

Up to now research has mainly focused on creating a mobile platform that could detect and map landmines in a given area to assist the demining experts, by presenting them a map with the locations of the landmines leaving to them the final part of removing the landmines.

Demining robots vary widely in their operating systems, locomotion systems, sizes etc. Navigation systems can be of two types; semiautonomous or autonomous. Semiautonomous means they still need human interference in their mission while autonomous demining system can perform all the stages, although very complex and expensive. In terms of locomotion there are plenty of solutions being developed and of all shapes and forms, quadrupeds, hexapods, wheeled, drones and even rolling systems.

A quadruped walking mechanical structure is the TITAN-IX robot. This robot is able to change working tools on the end of one leg allowing it to operate as a metal detector, scanning a small area while staying stable and then moving to the next location. Another quadruped is the SILO4 which has a similar working concept. Most of the demining robots working concept is pretty simple and self-explanatory as the demining robots' task is to simulate a man minesweeping with a metal detector.

Figure 2.1 - Quadrupeds (L) TITAN IX [16] and (R) SILO4 [17]

Another interesting demining robot, is the Teodor, a semi-autonomous search, rescue and demining robot. For demining missions the robot is equipped with a specialized multi-channel metal detector array and the robot is supported by an unmanned aerial system. The idea is to create a collaborative aerial + ground robotic demining platform, where the airborne platform scans the minefield from above for potential locations of landmines which are then confirmed by the ground robotic system.

Figure 2.2 –Teodor ground robot (Left) and together with the aerial support [18] (Right).

Below can be seen some of the robots that participated in the Minesweepers competition [19]: Towards a Landmine-Free World competition in 2012 and 2014. Some demining robots that participated in the competition are very simple, as any mobile robot holding a metal detector can be programmed to be a demining robot and others more complex, equipped with ground penetrating radars (GPR), infrared detectors or detectors for vapors from explosives like the ones can be seen below.

Figure 2.3 - Some of the participations from Minesweeper comp. 2012-2014 [19].

De-activating landmines is still a tough task for a robot, however there have been some solutions developed to use robots that would trigger the landmines by stepping on them like the Callum Cooper [20]. It works similarly to mechanical clearance, a wind-powered device that is heavy enough to detonate landmines rolls through the fields detonating the landmines. The advantages are easy transportation, cheaper than heavy armoured vehicles and no human participation. However triggering the landmines is in most cases undesirable as it has dire consequences on the land, besides that it always implies damage of material and especially for a robot that is not a heavy armoured vehicle which will be likely partially or totally destroyed. Constant rebuilding after explosions and the cost associated with it are other disadvantages of this robotic demining method.

Figure 2.4 - Mine Kafon demining prototypes for Callum Cooper, triggering a landmine [20] (Right).

The same company is working on a new prototype which solves the rebuilding and its cost. The autonomous Mine Kafon Drone [21], an unmanned airborne demining system that uses three step process to map, detect and detonate land mines. First the drone flies over a given area and identifies all the potential dangerous areas, then equipped with a robotic metal detecting arm the drone hovers above the ground to construct the map of known mine locations. Finally the drone attached with a robotic gripping arm, places a small detonator on every mine to then be detonated safely.

Figure 2.5 - Mine Kafon Drone mapping, detecting and detonating steps respectively [21].

2.2. Robotic demining arms

As was shown in the previous section most of the demining robots are still somewhat primitive in their arm manoeuvrability having most of them from 0 to 2 degrees of freedom. The main challenge of the researchers is to achieve high efficiency in landmine detection while avoiding false alarms, so at this stage they are just building, improving and testing their algorithms and mine detection sensors in planar terrains. When the detection technology is improved and acceptable for real life scenarios then the investment on locomotion and arm structure will begin. However few robots are already one step ahead and working on their locomotion and arm manoeuvrability like the two that will be discussed here.

The SILO6 [22] [23] is a six-legged walking robot (hexapod). It has a five DOFs manipulator equipped with IR range sensors which are placed around the metal detector. The robot also has other additional capabilities like EKF fusing, DGPS and odometry. SILO6's tailor-made manipulator is presented in Figure 2.7.

Figure 2.6 - The SILO6 [22].

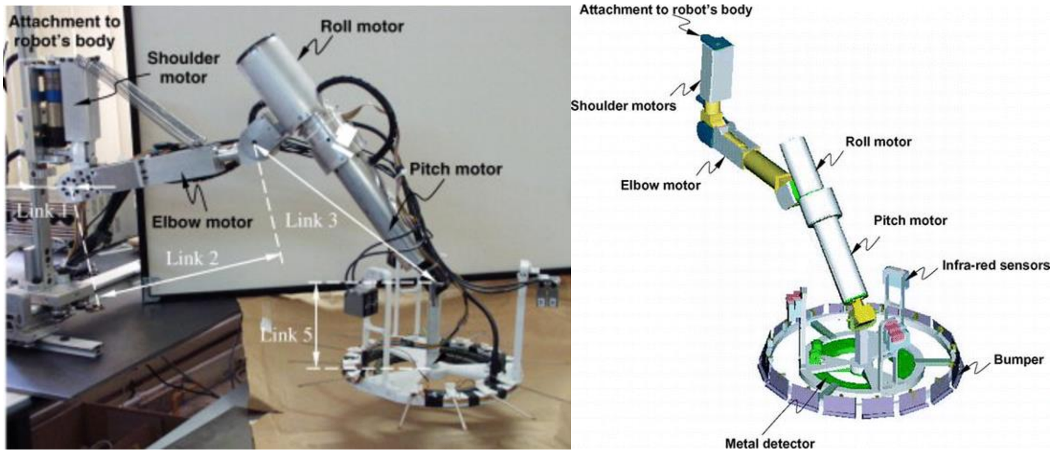

Figure 2.7 - Scanning manipulator and sensing head configuration [23]

In order to achieve the 5 DOFs, motors were put on the manipulator close to the metal detector which has metal parts. Additionally the cables connected to the motors conduct electricity which creates electromagnetic interference (EMI) and this interferes with the metal detector readings.

The other demining robot with five DOF is the Gryphon [24], which developed in the Tokyo Institute of Technology. It is a large four-wheel all-terrain vehicle that can be remotely controlled or manually driven. It has a long manipulator that consists of a counter-balanced pantographic arm with 3 degrees of freedom and a metal detector with 2 degrees of freedom in the wrist which allows to position the metal detector with respect to the ground and adapt to the terrain. The front part of the manipulator is entirely free of metallic parts to avoid reducing sensing sensitivity or influencing data reading; the wrist mechanism is mainly made of polyacetal, while the front link is made of glass fibre reinforced plastic (GFRP). The wrist motors are remotely located and linked through two rods.

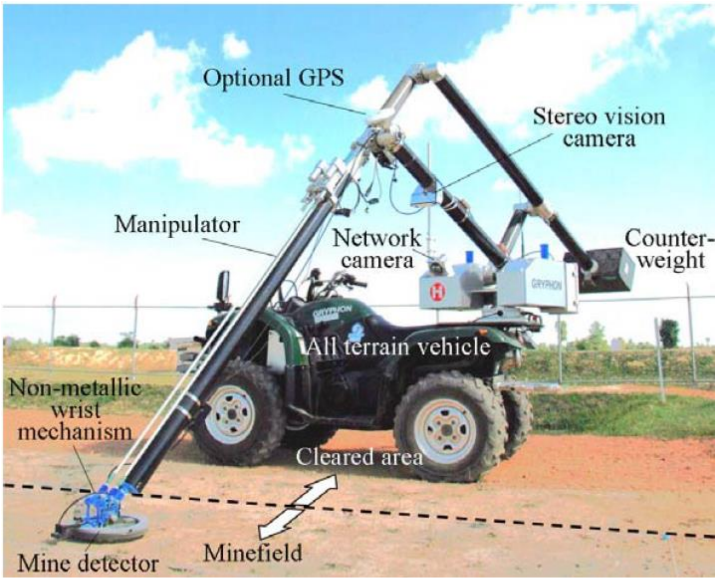

Figure 2.8 - Overview of the semiautonomous Gryphon system [24].

The use of rods to implement a linear movement is a simple and easy way to achieve the desired behaviour however it’s a rigid linkage intended for demining on flat terrains. In the case of the detector hitting an obstacle the rod could break or perhaps the motor could be damaged.

This state-of-the-art research came to the conclusion that most of the current demining arms were as advanced as ours with 2DOF. Those two presented above were the most advanced found, however they have some drawbacks that will be tried to improve in this project.

In order to add the desired degrees of freedom, the motors would have to be in the back and the actuators would have to be flexible to transmit the desired movement.

2.3. UC Demining Robot – FSR HUSKY

One of the contributions of ISR-UC team to the Tiramisu Project was the FSR Husky, an autonomous lightweight all terrain mobile ground demining robot. The robot is capable of understanding the characteristics of the terrain and navigating it avoiding obstacles and landmines. It is also able to detect mines and create a map with their locations marked.

The ISR-UC team finished the first version of the demining robot in 2012. However, the robot has been subject to various improvements over the years. It has also been tested on sample minefields as well as international competitions to benchmark its performance and identify the weaknesses.

Figure 2.9 - ISR-UC Robot in 2012 (Left) and 2015 (Right).

FSR Husky was the result of heavy customization of a skid steered mobile robot from Clearpath. The original robot was extended with a sensor bridge to host various sensors, like stereo cameras, laser with tilt unit and GPS antennas. A 4 DOF arm, with only 2 controllable degrees, was designed and build for FSR Husky at ISR-UC. The first joint of the arm, which is responsible for the sweep motion of the arm (motion around the yaw axis), is controlled by a brushless DC motor which is connected to the arm through a belt that allows sliding, in order to prevent any harm to the driving motor or the arm itself in case of collision with an obstacle. The second electronically controllable DOF rotates around the pitch axis, effectively adjusting the height of the metal detector. This motion is performed by a linear electric motor that controls the height of the arm, and this actuator is supported by an air shock to add compliance in the pitch axis against collisions. The arm is built like a parallelogram as was intended initially for flat surfaces. The other two degrees of freedom of the metal detector can be manually adjusted, changing the orientation of the end effector with respect to the ground. The customization added about 40 kg to the FSR Husky, making it weight now around 90 kg.

Figure 2.10 - The original metal detector, before it was mounted to the robotic arm [25].

2.4. Wire driven mechanisms

The mechanism selected to control the joints close to the metal detector, and the pitch mechanism, are wire driven actuating systems. Wires are light and flexible which is crucial for demining robots and they are also cheap. When wires are used as part of actuators, one end of the wire is connected to the motor and the other end to the end-effector. The challenge involved with this mechanism is to set wire paths, guide and protect them from the exterior while not allowing the wires interfere with the robots' demining task.

Wire driven mechanisms have been gaining wide notoriety in the last years, one example is the SKYCAM which is used to move a suspended camera in stadiums to provide different views of the game for fans. The camera platform is suspended on Kevlar ropes, connected to the corners of the stadium. The pilot operates the platform from the stadium using joysticks, in response to the joystick movements, the winches reel in and pay out the ropes, moving the camera up, down or side to side.

Figure 2.11 – Skycam

The complexity of a wire driven mechanism can vary drastically from a fishing rod mechanism to a robotic arm or leg. The ISR-UC team is also currently working on an adaptive under-actuated anthropomorphic hand [26]. In this case they use twisted spring actuators to push the fingers to close.

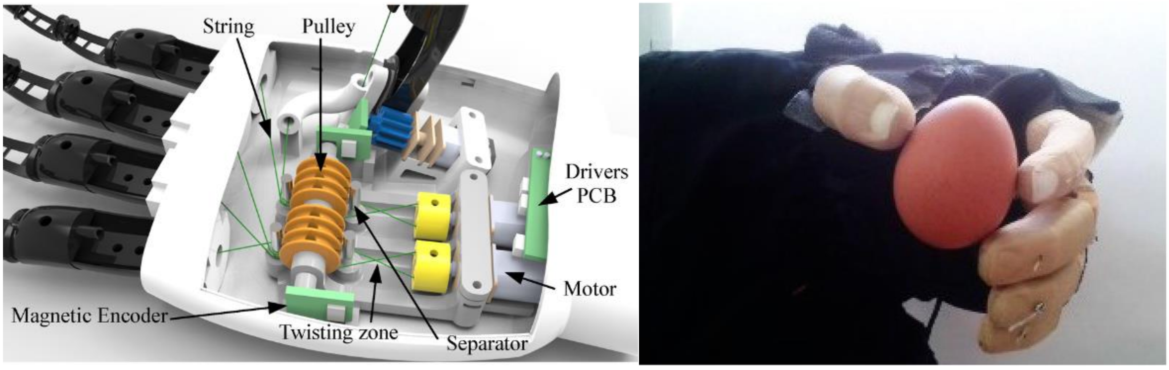

Figure 2.12 – 3D model of the UC-Softhand ISR-UC and performing a tripod grasp [26].

Wire driven systems can be very complex, especially in small spaces. The use of wire driven mechanisms are often associated with the means to guide them, like pulleys, springs or guiding rings which makes the implementation more complex. Another example of a wire driven mechanism, is the Roboy, an advanced humanoid robot developed at the Artificial Intelligence Laboratory of the University of Zurich. The 1.2m tall robot has tendon-driven systems for its locomotion and arm maneuvering, it uses cables with a degree of elasticity to act as muscles and tendons. To achieve this, there are 45 motors embedded in the robotic body to push on the wires and make the body move.

Figure 2.13 – Roboy, humanoid cable-driven robot.

2.5. Micro servo motors

In this work the motors will be micro servo motors because the torque needed for our mechanisms are small and micro servo motors are light and cheap. Servo motors are DC motors equipped with a servo mechanism for precise control of angular position.

Figure 2.14 – Micro servo motor scheme.

Servo motors are used for precision positioning, they can be applied in many applications, like for example directly on a robotic joint to create a DoF like shown in Fig. 2.15.

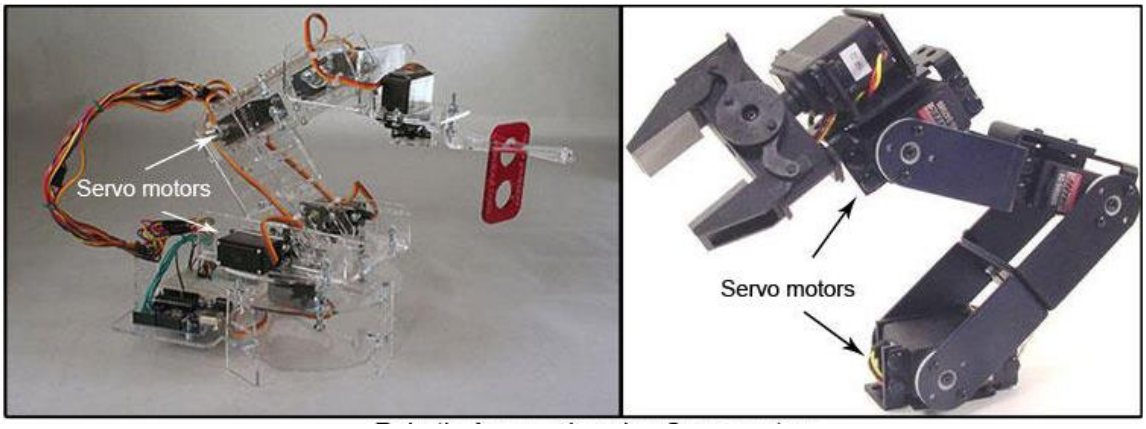

Figure 2.15 - Servo motors used in robotic arm to directly create a DoF [27].

Or with actuators connected, like wires or flexible tubes to control a mechanism or a degree of freedom like shown in Figure 2.16.

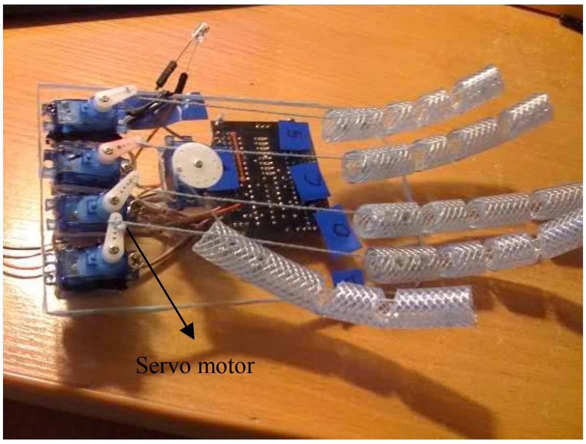

Figure 2.16 – Amateur robotic hand with 5 micro servo motors each connected to a finger [28].

One of the limitation of servo motors when used in wire driven mechanisms is that they can pull the wires towards them but cannot do the opposite. In order to achieve the opposite, another wire must be connected to the end-effector to do the opposite motion, this wire can be connected to the same servo motor or a new one. There are also other ways of achieving same results like using springs or if it’s a vertical motion to have it falling by gravity.

3. IMPLEMENTATIONS

One of the main limitations of the robot right now is that, only 2 DoF of the manipulator are electronically controllable. To improve this, a new tailor-made manipulator is needed. Motions of the metal detector in x and y are not independent, they are connected because the fixed length arm has to rotate at the yaw axis. In order to cover the whole x-y plane, the robot motion must also be used, otherwise the covered area of the plane is just an arc. Besides that, motion in the z axis is controlled through the pitch mechanism. These described yaw and the pitch motions of the arm together with the motion of the robot allow complete coverage of the plane. However, when uneven terrains are taken into account, the need for more degrees of freedom arise. These are integrated in the metal detector, which ideally would need just 2 DoF, in roll and pitch axis, for all kind of irregular terrain. However, a third DoF along the yaw axis is also added intending to change orientation of the metal detector to increase sweeping range and ease transportation. In transportation mode, to make the robot more compact, the metal detector is folded, and then when sweeping in order to increase the area you sweep, it's unfolded, making it parallel to the arm and sweeping different areas with the different coils it has.

However the implementations presented in this work aim only to build a 4 DOF electronically controllable manipulator. The reason is that, the existing robot arm already has those 4 DoFs, but it is missing the control to the yaw and roll DoFs. Adding the 5th DoF would mean destroying the original metal detector joint to replace it with a new more complex one, to allow 2 DoF. Besides the addition of the two new DoFs, this work aims to do some improvements weight wise, to completely redesign the initial two DoFs and to study the current components, in order to boost the FSR Husky performance.

In this work, it was decided to use a wire driven mechanism to control all the DoFs except the first yaw DoF. Wire driven mechanisms make the arm metal-free, which is important for the metal detector readings. Additionally the components are much lighter than any other option and are flexible. However wire driven mechanisms have challenges associated like optimized servo positions, wire length, incidence angles and path to guide and protect the wires.

To guide the wires, there will be several guiding rings, the wire is free to slide inside. The development of a new arm required new components, some which were already available in the lab, and some that could be made in the lab using the available 3D printer. The links used in the arm were already in our possession, one is made of carbon fiber and the other one is from a fishing rod which is made of a strong plastic. The joints, the guiding rings and the counterweight along other components were made in the lab's 3D printing machine, using ABS as material.

Figure 3.1 - Guiding rings used, horizontal link (Left) and vertical link (Right).

The selected wire is made of Kevlar. Slipping friction of the wires on the counterweight, joints and guiding rings which are made of ABS could slowly damage the plastic. In order to solve this problem, ceramic eyelets were added to places in the friction zones and the plastic was strengthened by bathing it in epoxy resin.

Figure 3.2 - Ceramic eyelets for friction (Left) and epoxy resin coating kit (Right)

In Figure 3.3 can be seen a global overview of the proposed arm and its components which will be discussed in the next sections. The arm base and the counterweight components will be explained in section 3.2 and 3.3 respectively.

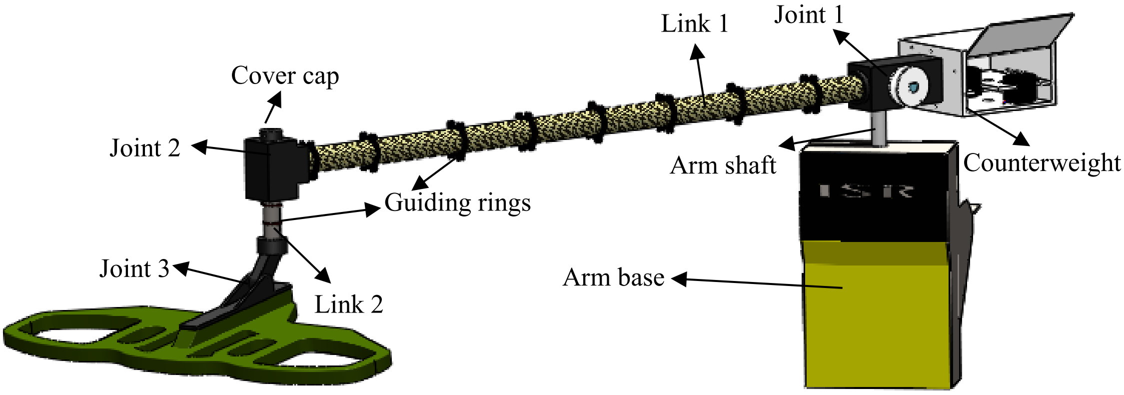

Figure 3.3 - Global overview of the arm.

3.1. Sweep mechanism

As stated before the existing robotic arm is driven by a DC motor in 2-D (in both directions, left and right) around the yaw axis, and the arm and the motor/gearbox are coupled with a belt. The belt provides compliance, hence when the arm hits an obstacle, the motor continues rotating but the arm doesn't move (the belt just slips around the pulley of the arm), and neither the arm nor the motor are harmed. In this work the motor and the arm are directly coupled with a safety clutch providing the same fail-safe mechanism. The main advantages of doing so, are that the reduction in the complexity of the current mechanism which involves many components whose weight is significant, and reduction in the space needed to connect them, which makes the metal sheet forming the arm base connecting arm sheet bigger and therefore heavier.

Despite this being a small application to transmit a small torque value, most of the commercial products, both clutches and brakes were out of our budget. The cheapest option available was using an electromagnetic clutch which had a major drawback. Electromagnetic clutches consume power continuously, around 15W for the 7.5 Nm and 20W for the 15 Nm model. This meant depleting the LiPo battery in less than 5 and 4 hours respectively, with just the clutch connected, nothing else (no motor, no pc).

Figure 3.4 – Intorq Electromagnetic clutch [29] (Left) and ECSK friction clutch [30] (right).

Ideally the mechanism should be automatic and mechanical, not requiring any power source to function. The remaining option was to build a custom clutch for the robot, after a state-of-the-art research on brakes and clutches, the clutch illustrated in Figure 3.5 was designed.

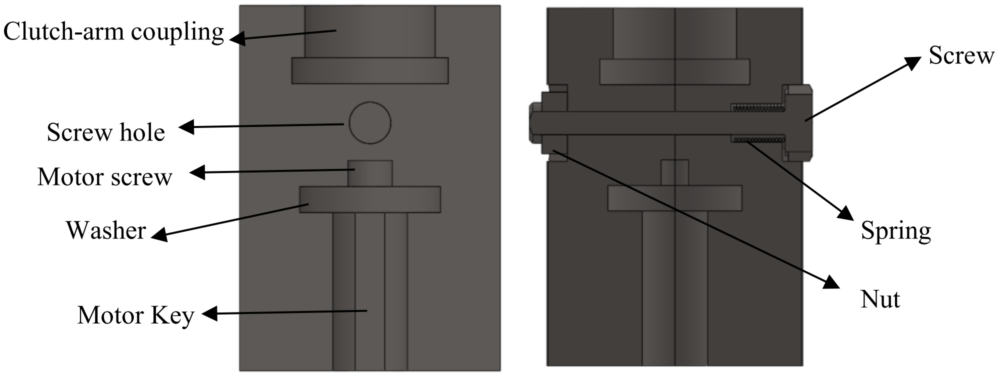

Figure 3.5 - Illustration of the custom clutch.

As can been seen from above the upper part has space for a shaft with a bottom disk, which corresponds to the robotic arm side. To keep the arm shaft adaptable for future changes instead of having a disk bottom, the project will have a coupling with a disk base to couple the arm shaft to the clutch.

On the bottom there is a setup for the motor shaft and its key, above it has a space for the gearbox's screw with a washer. The reason for this is to fix the clutch, not allowing it to be dissembled by pulling it up.

The clutch will be tightened by a screw and a spring allowing the arm shaft to rotate simultaneously with the motor shaft, but to keep it loose enough that if the arm is to hit something the disk has room to be loose, preventing it from damaging the arm or motor.

Initial tests done with the 3D printed prototype are promising, though still some adjustments and improvements are necessary.

3.1.1. Sweep motor and gearbox

The torque needed from the sweep motor is calculated by the 2nd Law of Newton for rotation.

$$\tau_{net} = I \times \alpha \qquad (1)$$

Where α is the angular acceleration and is taken to be equal to 1 rad/s in all degrees of freedom, I is the moment of inertia of the rotating components (the arm) with respect to the rotating axis and τ_{net} is the net external torque. The moment of inertia is 0.8 kg.m^2 hence the torque needed is 0.8 N.m, considering a safety factor of 2.5 the selected motor would need a torque of 2 N.m. The current motor was in our possession from a previous robot and is the same as the assembled one in the existing arm, with a torque of 3.54 N.m and 1.5 kg. Although the motor is over dimensioned, it was decided to stick to it in order to save money.

It was also considered to remove the gearbox to reduce the weight since the motor torque is more than enough, and the gearbox weights approximately 1.1 kg. However the disassembly is complex, requiring paid assistance from the provider. Besides that the gearbox is needed for speed control. Controlling DC motors at low speeds is difficult, so with the gearbox, we can drive the motor at higher rpms, where it is easy, but have the small and exact rpm/position value at the output.

Figure 3.6 - Robot motor and gearbox.

3.2. Arm base

The main concern about the arm base is its connecting sheet, it is over dimensioned in thickness resulting in extra weight for the arm. In addition, the connecting sheet has a box, like enclosure, to protect the inside components from the exterior, so the bigger the dimensions of the connecting sheet the bigger are the rest of the sheet components significantly increasing the total weight of the robot. The existing arm base is shown in Figure 3.7.

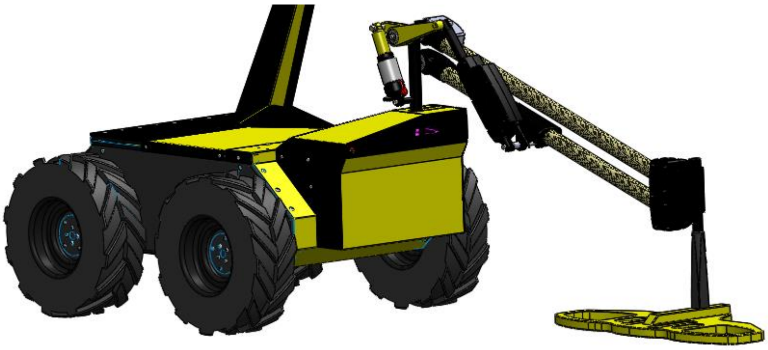

Figure 3.7 - Illustration of the Husky arm base.

The current connecting sheet is made of steel, has around 6 mm thickness and weights approximately 6 kg. The remaining sheets have 2mm thickness which is fine as their function is just to cover the box. Therefore weight can be reduced by minimizing the main sheet dimensions and thickness.

The new connecting sheet is T-shaped, the reason for this is that the sheet had to be extended to provide vertical space to connect a bearing to carry the arm shaft. The new arm base is shown in Figure 3.8

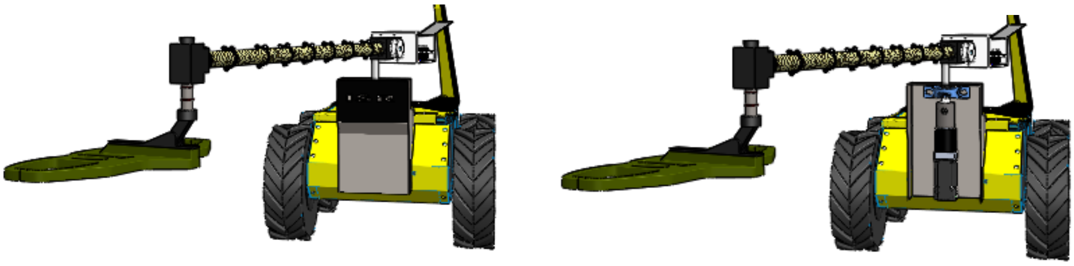

Figure 3.8 - New arm base.

The new arm box weights 4 kg, meaning a 40% weight reduction of the existing the box. The thickness selected is explained in 3.2.1, where a stress analysis of the arm base was performed to find the optimum thickness.

3.2.1. Arm base stress analysis

In order to dimension the connecting sheet, stress analysis was made using Solidworks static simulation. To find the optimum main sheet thickness, the thickness was varied and the stress was estimated.

In Figure 3.9 a 1mm thickness sheet was analyzed in the stress simulation, showing that the maximum stress is 150 MPa in few zones of the vertical top part of the main sheet which was expectable since that’s where the bearings are holding the arm. The value obtain of 150 MPa is quite significant as the yield strength of steel is around 200MPa, depending on the steel alloy.

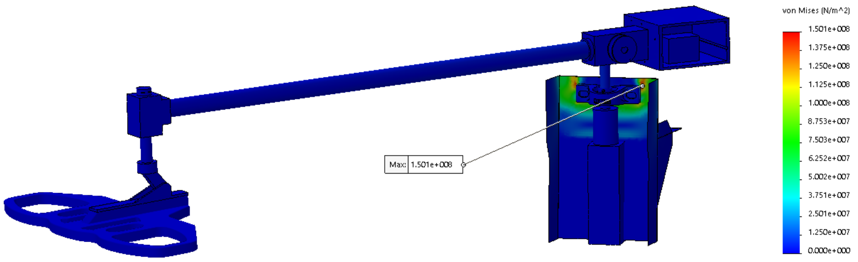

Figure 3.9 - Stress analysis for 1mm thickness.

Taking into consideration the possible future alterations and a high safety factor, the thickness chosen was 3mm with a maximum stress of 25 MPa as can be seen in Figure 3.10.

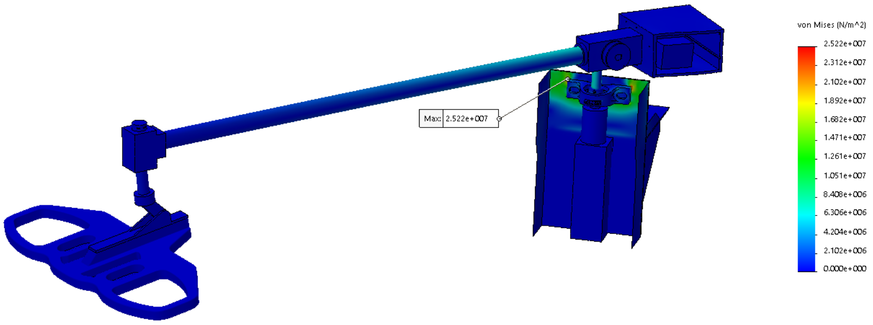

Figure 3.10 - Stress analysis for 3mm thickness.

3.3. Servo motors degrees of freedom

In order to keep the wire paths simple, all the motors are located in a counterweight box behind the pitch joint.

The wires leave the counterweight through holes and go directly to the guiding rings until their destination. There are two zones where the wires are not guided and are exposed which can be seen in Figure 3.11. The first zone is right after leaving the counterweight where the wires are loose on the top and bottom of the joint. The second zone is for the roll wire after changing from link one to link two. The initial plan was to have the joint with holes inside to guide the wires until the guiding rings. However the precision of the 3D printing machine did not allow that. Nonetheless, this should only be a problem if something was to fall/hit on the wires but that would be a problem everywhere in the arm as they are not protected from the outside. Protecting the wires from the exterior would be challenging and complex as there already are cables going through the inside of the links and making them bigger or extend the guiding rigs throughout the length of the links would be very complex. The second zone was initially designed with a pulley on the joint to facilitate motion of the wires. However this increased complexity of that joint, having it directly connected between the links shouldn't be an issue since the motor will be over-dimensioned but either way both zones can be improved once the tests begin.

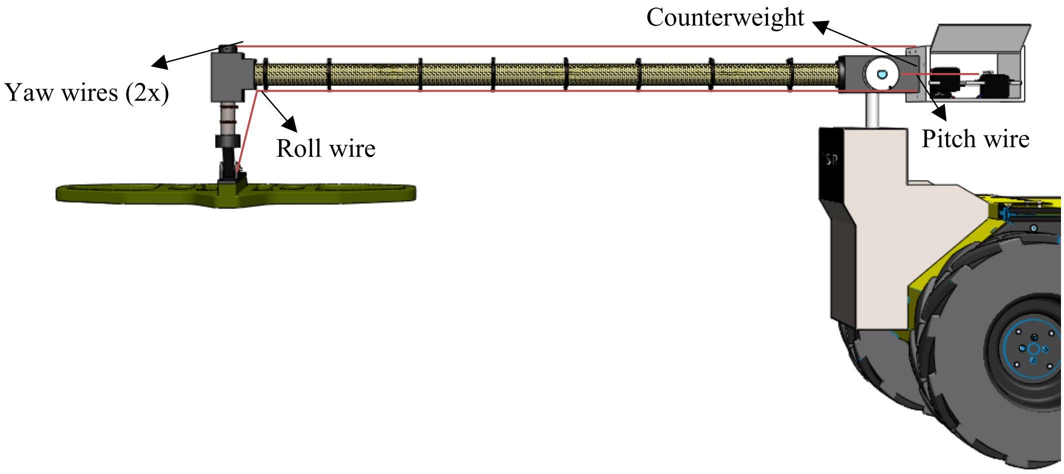

Figure 3.11 – Illustration of the arm structure.

The servo-motors inside the counterweight are fixed with screws to a portable connecting sheet that can be fixed to the box. The counterweight has also a cover that can easily be opened, to remove or put the servo motors and to keep them protected from the exterior conditions, such as wind, dust, snow while sweeping for mines in a minefield. The electric cables of the motors go down through a hole in the counterweight box to the base of the husky. To facilitate the connections the roll motor is placed upside down as the hole in the counterweight is on the bottom and that wire is guided on under link 1.

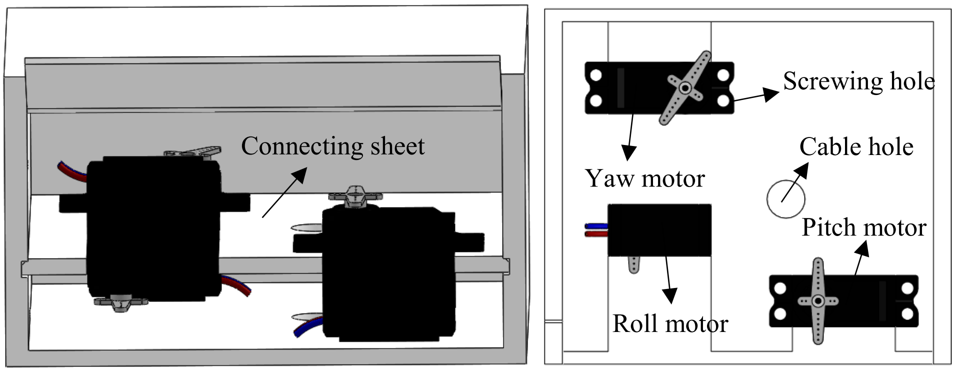

Figure 3.12 - Counterweight composition.

It is assumed that there are losses due to friction and other factors in the wire system and with that in mind along the fact that there will be future alterations and improvements, the micro servo motors selected are over dimensioned. The torques needed are not too high and over dimensioning is not a bad thing in this case, micro servo motors are relatively cheap and light.

3.3.1. Pitch mechanism

The pitch is one of the controllable degrees of freedom of the existing manipulator. It was controlled by a linear electric motor that indirectly controls the height of the arm, and supported by an air shock to add compliance to the pitch axis in case of collisions. This mechanism had several issues, like creation of vibrations, slowness and high weight. This mechanism has heavy components, so instead of re-dimensioning the current electric linear motor, the idea of changing that mechanism to reduce the weight was very appealing.

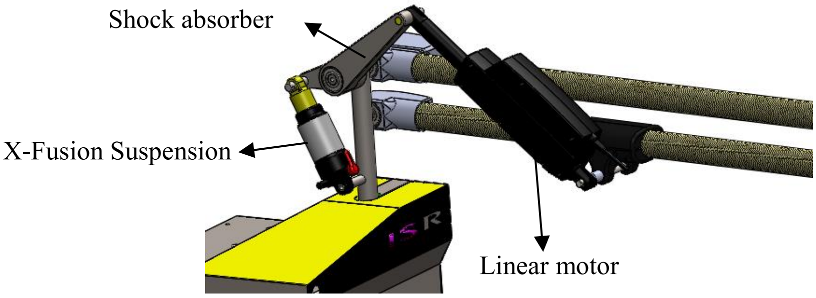

Figure 3.13 - Husky current pitch mechanism.

The existing pitch mechanism is also responsible from keeping the arm floating at a safe distance when Husky is not working, maintaining the height and not letting the arm hit the robot or the floor. Replacing this mechanism for a wire driven mechanism has a main disadvantage and it is losing this capability. In order to prevent the arm to be on top of Husky or touching the ground, a simple adjustment can be made to add a portable arm holder to the robot to hold the arm while the robot is being transported or is offline.

The micro servo-motor on the counterweight has a wire reeled on itself and connected to the pulley as can be seen in Figure 3.14. The pulley is on the side shaft, which is fixed and has a cut so the pulley doesn't rotate. The mechanism is simple, when the motor releases wire the counterweight goes up due to the left side being heavier and when it pulls the wire the counterweight goes down. Behind the pulley the setup is similar to the existing one, a plastic joint with two ball bearings to hold the side shaft and allow the pitch motion.

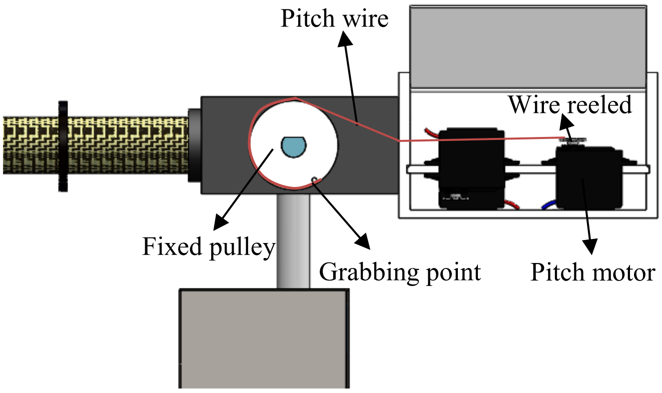

Figure 3.14 - Pitch mechanism illustration.

Calculations of the static moment on the pitch axis are presented below:

$$M_A = F_{left} \times d_{left} - F_{right} \times d_{right} \tag{2}$$

In this case the forces are the mass of the components multiplied by the acceleration of gravity and d are the distances from center of gravity, in this case to simplify the calculations it's used the farthest point of that side to the rotating axis.

Left side of the rotating axis:

$$Mass = 0.766\ kg$$
$$D_{left} = 1\ m$$

Right side of the rotating axis:

$$Mass = 0.636\ kg$$
$$D_{right} = 136\ mm$$

Resulting in a moment of $M_A = 6.77 N.m$ for the left side. In order to balance this moment, a $5\ kg$ counterweight could be added, a spring mechanism could be used, or counterweight distance could be extended. Extending the distance of the counterweight was not feasible because it would make the arm hit the antenna bridge behind it. Increasing the weight of the arm would increase weight of the arm, hence this was not an option either.

In order to dimension the pitch motor, the torque needed must be calculated through the 2nd law of Newton applied to rotation systems, previously stated at 3.1.1:

$$\tau_{net} = I\ \times \alpha$$

Where α is the angular acceleration and it is equal to 1 rad/s in all degrees of freedom, I is the moment of inertia of the rotating components in relation to the rotating axis and τ_{net} is the net external torque which is equal to:

$$\tau_{net} = \tau_{motor} - M_A \tag{3}$$

The moment of inertia of the arm can be roughly estimated using the following formula:

$$I = \sum_{1}^{n} m \times r_i^n \leq M \times {r_n}^2 \tag{4}$$

Where M is mass of the components and r_n is the distance from the farthest horizontal point of the component to the rotating axis. The total inertia of the rotating components is 0.77 kg/m^2. Replacing values in eq. 4 then we obtain:

$$\tau_{motor} = I \times \alpha + M_A = 7.544\ N.m \tag{5}$$

This torque is quite significant for a micro servo motor, however the actual torque needed from the servo motor is explained below.

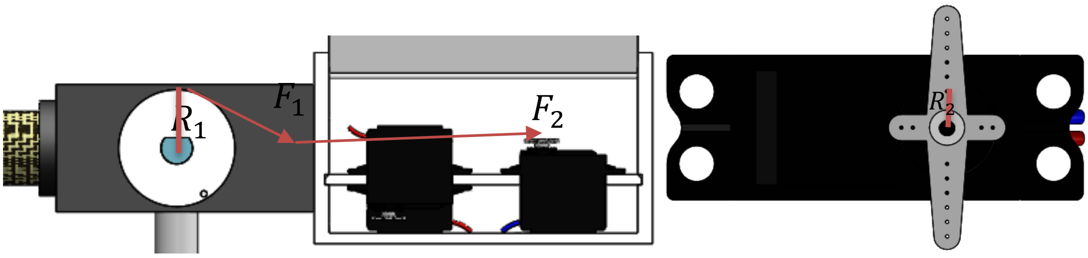

Figure 3.15 - Pitch force and radius illustrations

From the Figure 3.15 can be stated that F_1 and F_2 are the forces of the wire in the pulley and servo motor, respectively, and that they are equal:

$$F_1 = F_2 \tag{6}$$

Where both F_1 and F_2 are equal to eq. 7 with their respective radius and torques:

$$F = \frac{\tau}{R} \tag{7}$$

Combining eq. 6 and 7 and solving to find the torque needed from the servo motor, with the radius of 27.5 mm and 8mm, for the pulley and micro servo motor bracket respectively, and the torque at the pulley previously calculated in eq. 5 then the torque needed is equal to 2.19 N.m.

The selected micro servo motor has a torque of 4.7 N.m which gives a safety factor of 2.11. If taken into considerations the overestimated moments in eq. 2 and the inertias in eq. 4 this servo should be enough to compensate the eventual losses in the paths such as friction. This was the highest torque needed which is a value relatively high for micro servo motors, the price was still affordable and very light weighting only 300g.

3.3.2. Yaw mechanism

Although the current arm does have the yaw degree of freedom, it is not electronically controllable, but manually controllable.

The main goal of this degree of freedom is to set the metal detector to a home position electrically, thus saving time and effort to do this manually. This is particularly useful when the robot is not mine sweeping and needs to occupy less space when to be transported, like in an elevator or a van for example.

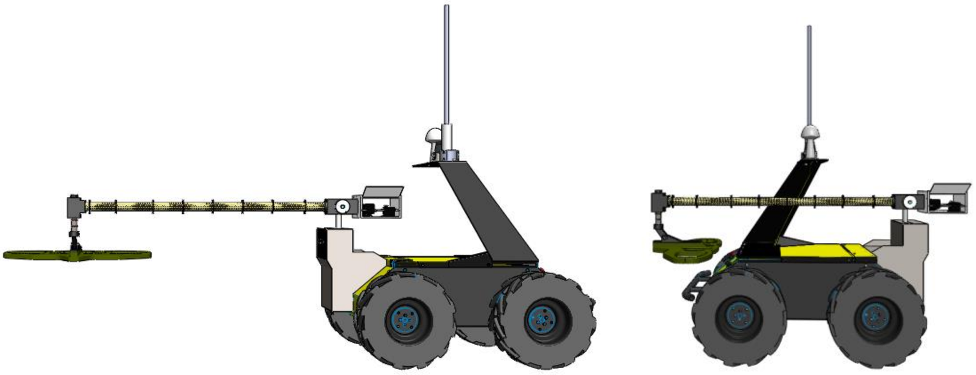

Figure 3.16 - Illustration of the working position (Left) and Home position (Right).

The working position of the robot is shown in Figure 3.17 for faster coverage of the x-y plane hence the degrees of rotation needed are 90º.

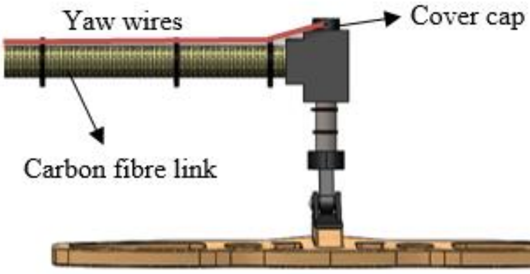

Figure 3.17 - Illustration of the metal detector working position.

The micro servo motor controlling this joint is located in the counterweight. The controlling wires go from the counterweight to the guiding rings on top of link one until the end-effector, which is the cover cap of link two. The cap is also responsible from holding the link on the joint so it doesn't fall. Link two is free to rotate inside the joint without inside friction.

The servo motor has a cross bracket, the bracket has two wires attached one at each side like can be seen in Figure 3.18. The wires go through the guiding rings until the end-effect that has a similar setup. So when the motor rotates βº the end-effector will rotate βº accordingly, assuming the diameters are equal. This mechanism actually allows 180º degree control (+90º and -90º).

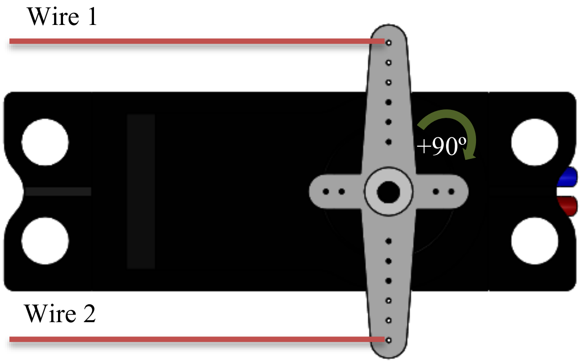

Figure 3.18 - Illustration of the yaw mechanism in the micro servo motor.

The torque needed can be calculated from the 2nd law of Newton for rotational systems stated before in eq. 2 where τ_{net} in this case is equal to:

$$\tau_{net} = \tau_{motor} - \tau_{surf.friction} \tag{8}$$

Where $\tau_{surf.friction}$ is the torque needed to compensate the surface friction between the yaw end effector, the cover cap, and the joint below where the cover cap lies. It is calculated by the adaptation of the following equation, which is for the rotating friction of a disk on a horizontal surface.

$$\tau_{surf.friction} = \frac{2M\mu g}{R^2} \times \int_0^{R_1} r^2\, dr \tag{9}$$

Where M is the mass, R is the radius, μ is the coefficient of kinematic friction between the surfaces. Integrating and assuming $\mu = 0.4$ for plastic-plastic, we obtain a torque friction on the surfaces equal to $3.22 \times 10^{-3}\ N.m$.

Inertia is calculated by the same logic applied previously and it is equal to $0.0222\ kg/m^2$.

Putting in eq. 1 we obtain:

$$\tau_{motor} = I\ \times \alpha + \tau_{surf.friction} = 0.025\ N.m \tag{10}$$

The torque needed is very small and the selected micro servo motor for this mechanism has a torque of 1.3 N.m, which is significantly superior, with a safety factor of 52. However the difference of buying a weaker servo of this magnitude compared with the one selected is of few euros and few grams hence the selection.

3.3.3. Roll mechanism

The current metal detector was initially a hand metal detector which already had the roll degree of freedom however it was not controllable. It is very common on hand metal detectors as they can be used for other purposes than demining like prospecting for valuable metals and coins. The reason for this is that most of these non-demining activities for the hand metal detectors can allow the user to push and move the metal detector against the ground and having it mechanically adapt to the terrain. However in demining the weight/pressure of the metal detector could make the landmine detonate hence the metal detector has to be always above ground level.

The response of the metal detector depends on the distance of the target object. Additionally the sensitivity of the metal detector decreases with increasing distance of the target. Therefore a controllable roll mechanism benefits demining by helping keep the metal detector as close as possible to the surface. The range of rotation degrees needed is not a factor as the ground is not expected to be too inclined, about 45° variation from ground level should be enough for most of the minefields.

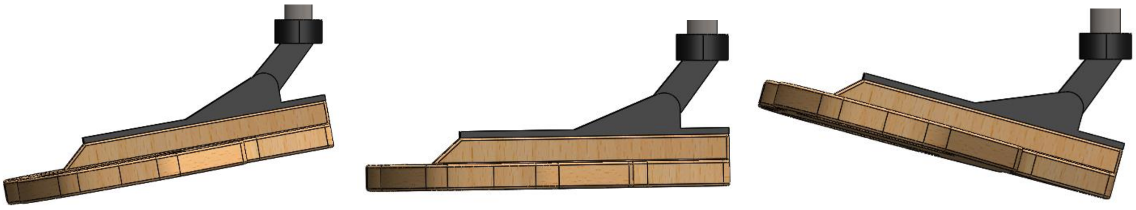

Figure 3.19 – Illustration of the roll motion.

To create the 4th DOF, the mechanism will work similar to the pitch mechanism. One motor with wire reeled will push or let loose by rotating to either side. When the detector is to elevate, the motor pulls the wire and when released the metal detector falls due to gravity.

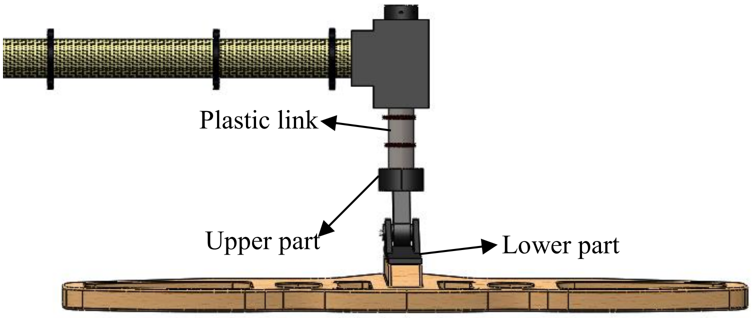

Figure 3.20 - Illustration of the roll mechanism.

As can be seen from Figure 3.20 and Figure 3.21, joint 3 is composed of an upper and lower part which are connected through a concentric cylinder in order to allow the metal detector to rotate around that axis. In order to fix the cylinder to the metal detector to fix their movement, they are screwed using a plastic screw where the wire will be connected.

This is a tricky mechanism to program because when the yaw motor is rotating the roll wire must be loose or pulled accordingly depending into which position the yaw is moving so the metal detector height is not compromised nor the wires.

The torque is calculated similarly to the previous ones, following eq. 2, in this case the net torque is equal to:

$$\tau_{net} = \tau_{motor} - M_B \tag{11}$$

Where M_B is the static moment at B, the rotating axis, caused by the center of mass of the rotating components as can be seen below:

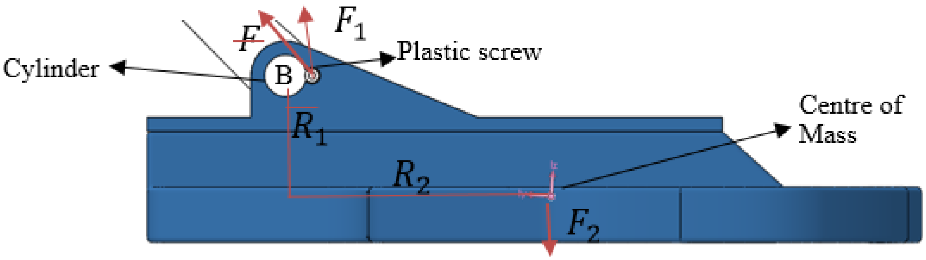

Figure 3.21 - Roll static moment illustration.

Where F is the wire force, F_1 the vertical component, assuming 45°, and F_2 the weight load of the rotating components. Their distances to the rotating axis are, 9.6 mm and 90 mm respectively and the mass of the components is equal to 290 grams.

Using eq. 2 to calculate M_B:

$$M_B = -F \times \sin 45 \times 0.009 + 0.290 \times 0.09 = -F \times 0.009 + 0.0261 \tag{12}$$

From eq. 7, F can be put in equation 12 to obtain:

$$M_B = -\frac{\tau_{motor}}{0.008} \times 0.0063 + 0.0261 = -5.3 \times 10^{-5} \times \tau_{motor} + 0.0261 \tag{13}$$

Combining equations 13 and 1 we obtain:

$$\tau_{motor} - (-5.3 \times 10^{-5} \times \tau_{motor} + 0.0261) = I \times 1 \tag{14}$$

Where the inertia was calculated like in the previous sections and it is equal to $0.018\ kg/m^2$.

$$1 \times \tau_{motor} = 0.018 + 0.0261 = 0.0441\ N.m \qquad (15)$$

The τ_{motor} needed is $0.0441\ N.m$. The selected micro servo motor for this mechanism is the same as the previous, with a torque of 1.3 N.m, resulting a safety factor of 29.

4. CONCLUSION AND FUTURE WORK

The major challenges in building a robotic demining arm is adding compliance and keeping the arm metal free. Compliance helps to protect the arm from any harm due to collisions with obstacles or the surface. Metal, when close to the metal detector, interferes with its functioning, reducing its sensitivity, and even making it blind to landmines. Therefore the mechanisms have to be flexible and the joints close to the metal detector should not have metals attached or surrounding them. It is important for the metal detector carrying arm to have more than two controllable DoFs, especially if it is going to be used on non-flat terrains. Therefore, future efforts should be made to implement similar mechanisms to the one presented in this work in all demining robots.

The wire driven mechanism has several advantages. It is flexible, cheap and light. However keeping the wires protected, guided and stretched to achieve high performance can certainly be a complex task.

The new arm weighs 45% of the existing arm, weighting approximately 9 kg. This is drastic decrease in weight and it will boost the energy efficiency of the robot, extending its battery life as well as decreasing wear. Further improvements to the weight are still possible, and these could be achieved by optimizing the material used in the sheets and other components.

After building and testing the arm, the need to implement a 5th degree of freedom in the pitch axis of the metal detector may arise. This can be achieved by introducing a new joint or replacing the final joint with a ball joint. This would also require some changes in the wire drive mechanism. Quality of the arm could be improved by improving the 3D printing process, using stronger materials with a more professional 3D printer.

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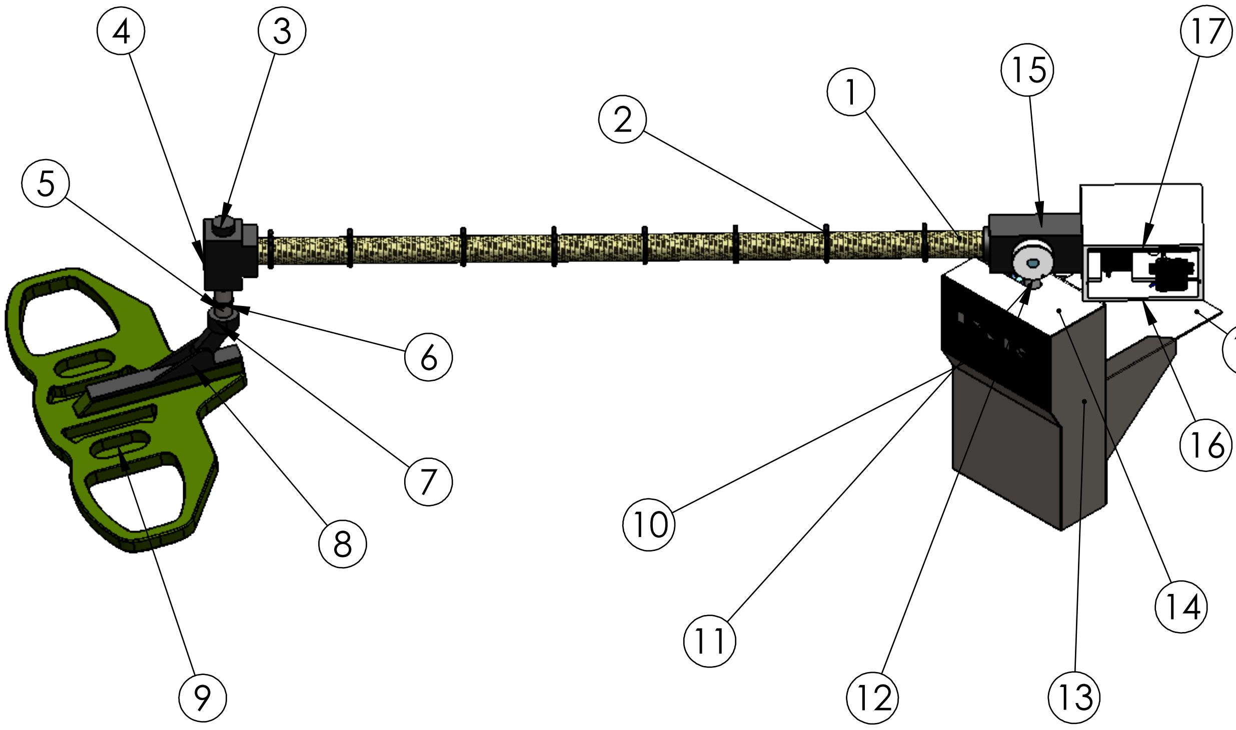
APPENDICES

Nº	Components
1	Carbon fibre link
2	35mm Guiding Rings
3	Cover cap
4	Joint 2
5	Plastic link
6	25mm Guiding Rings
7	Upper part of joint 3
8	Lower part of joint 3
9	Metal detector
10	Front sheet

Nº	Components
11	Arm shaft
12	Pulley
13	Lateral sheet
14	Top sheet
15	Joint 1
16	Counterweight box
17	Counterweight window
18	Connecting sheet



MATERIAL:

Title: Arm

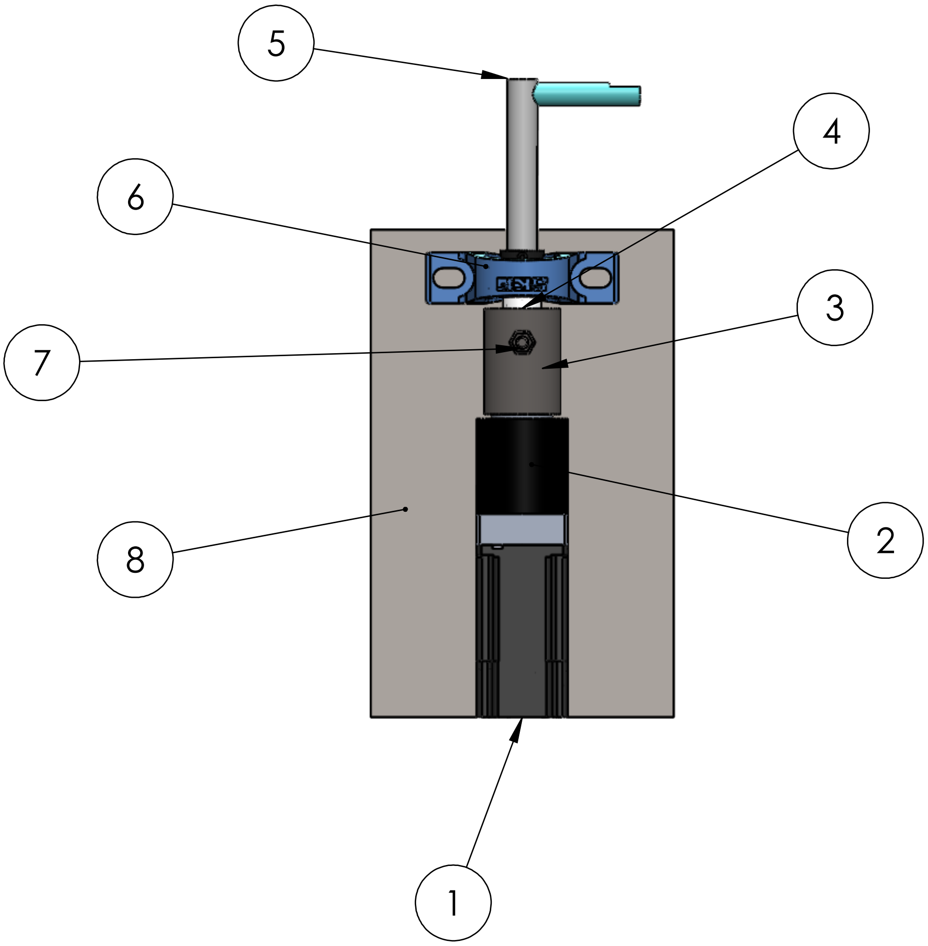
A4

TOLERANCE:

SCALE:1:50

SHEET 1 OF 1

Nº	Components
1	Motor
2	Gearbox
3	Clutch
4	Clutch-shaft coupling
5	Arm shaft
6	Bearing
7	Screw, spring and nut
8	Connecting sheet



MATERIAL:	Title: Arm base	A4
TOLERANCE:	SCALE:1:5	SHEET 1 OF 1