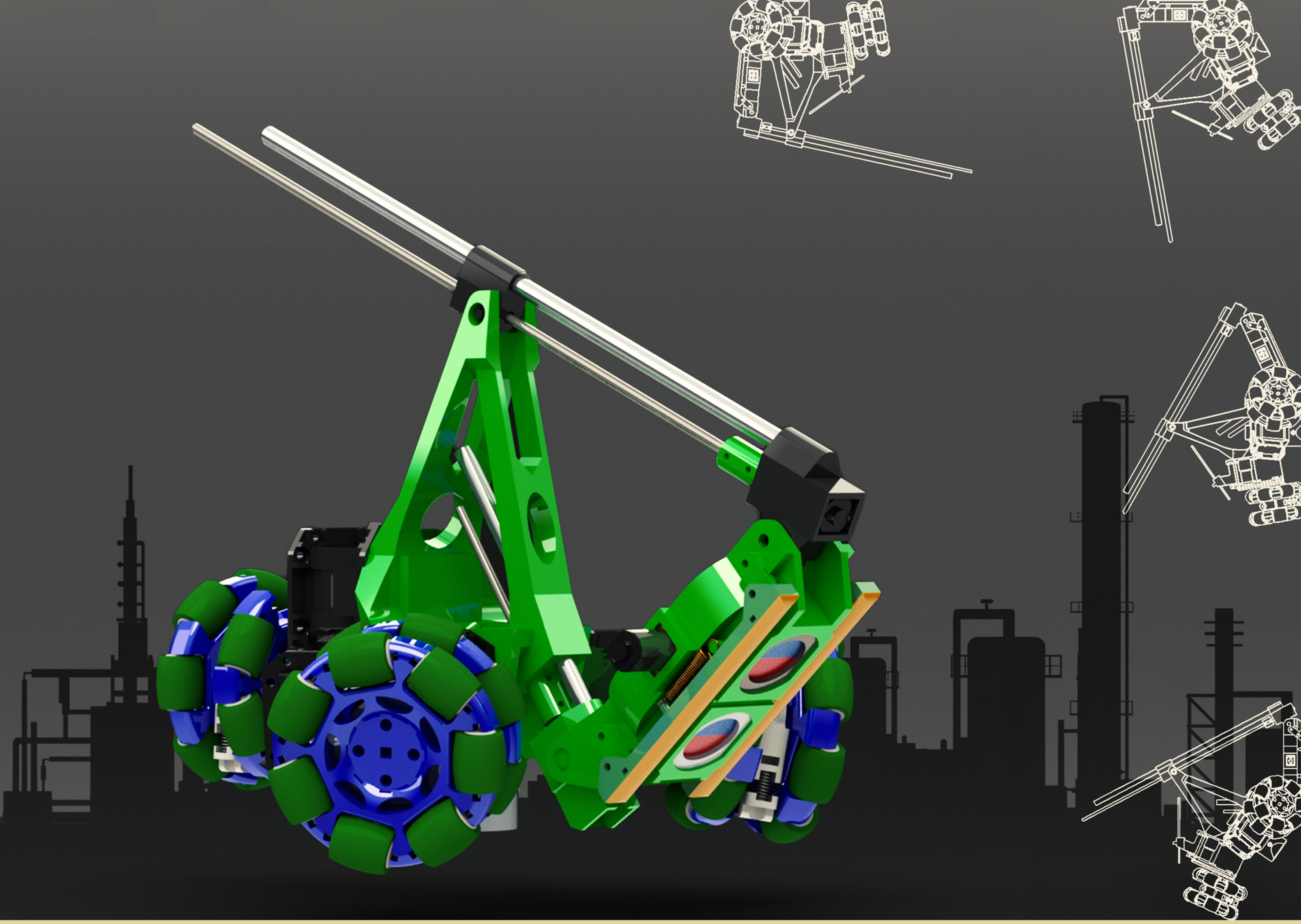

João Luís Ministro Lourenço

The hybrid OmniClimber robot: Wheel based climbing, arm based plane transition, and switchable magnet adhesion

Dissertation presented to achieve the degree of Master in Mechanical Engineering
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Universidade de Coimbra

FCTUC FACULDADE DE CIÊNCIAS
E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

DEPARTAMENT OF MECHANICAL
ENGINEERING

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Abstract

Climbing robots that integrate an articulated arm as their main climbing mechanism can eventually take advantage of their arm for plane transition and thus to operate on 3D structures rather than only climbing planar surfaces. However, they are usually slower than wheel based climbing robots. Within this research we address this problem by integration of a light-weight arm and adhesion mechanism into an omnidirectional wheel based climbing robot, thus forming a hybrid mechanism that is able to perform plane transitions and remains an agile climber.

A two degrees of freedom, four-bar linkage mechanism was designed as a light-weight arm for the transition mechanism. In the four-bar linkage, two of the bars are actuated and have variable length. Furthermore, we customized and developed actuated switchable magnets both for the robot chassis and also as the adhesion unit of the arm. These units allow us to control the amount of magnetic adhesion force, resulting in better adaptation to different surface characteristics. The adhesion units are safe for climbing applications with a very small power consumption. The conceptual and the detailed design of the mechanisms are presented. The robots were developed and successfully tested on a ferromagnetic structure.

Keywords. Climbing robots, climbing mechanism, plane transition, omnidirectional, wheel based, switchable magnets, ferromagnetic structure.

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LIST OF ABBREVIATIONS

Symbology

d Distance between the Adhesion Unit and the anchor point

T_W Torque generated by the weight

D Distance between the center of mass and the anchor point

F_W Weight of the robot

T_{AU} Torque generated by the Switchable Magnets

F_{SM} Force generated by the Switchable Magnets

s Distance between Switchable Magnets

F_a Friction force

W Weight

M Force required to move

l_1 Length of the top bar

l_2 Length of the bottom bar

F_{out} Axial force generated by the threaded shaft

η Efficiency

T_{in} Torque of the motor

p Pitch of the threaded shaft

Acronyms

SM Switchable Magnets

RoMeLa Robotics and Mechanisms Laboratory

DOF Degree of Freedom

SRI Stanford Research Institute

CMU Carnegie Mellon University

AISI American Iron and Steel Institute

ARM Advanced RISC Machines

TTL Transistor-Transistor Logic

UART Universal asynchronous receiver/transmitter

TX Transmission

RX Reception

ID Identification Data

PWM Pulse-width modulation

SPI Serial Peripheral Interface

PC Personal Computer

1 INTRODUCTION

Climbing robots have been developed and widely used in industry in the last couple of decades, to respond to the need of a tool capable of performing specific work of inspection and maintenance. Complex industrial facilities as that shown in Figure 1 are the places where most climbing robots are used.

Figure 1: Typical environment of application of climbing robots. Oil refinery in Louisiana

Besides inspection they perform repairs, painting cleaning and other maintenance tasks in hard to reach hazardous locations. The Omniclimber appears to try to fulfill this need with a novel concept for an inspection robot for industrial purposes. The motivation of this work is to empower and continue to equip Omniclimber. At the beginning of this study we had Omniclimber already able to climb and navigate over flat and curved ferromagnetic structures robot, yet it has still many things to improve. The improvements to the Omniclimber were made taking into account the following three main objectives:

- Weight reduction.
- Development of a capable transition system.
- Replacement of electromagnets by switchable magnets (SM).

Weight reduction allows to increase the load capacity, improve energetic efficiency and the maneuverability of the robot.

The transition system gives the robot autonomy, allowing it to operate in complex structures and move between surfaces without human intervention.

The replacement of electromagnets by switchable magnets was initiated in a previous work with the development of specially designed for robotics application switchable magnets but their implementation was still not done and so it is one of the objectives of this work.

This document starts by addressing the theme and the goals of this research. The second chapter presents and discusses the locomotion and the adhesion mechanisms used in climbing robots. The third and fourth chapters are about the old and new versions of Omniclimber. The fifth chapter contains the tests performed and the results obtained.

Finally, conclusions are presented and is made an overlook on all the achievements on this research. Improvements to be implemented in future work are also mentioned in this chapter.

1.1 Motivation for the use of Climbing Robots

Inspection and maintenance are basic needs for modern industries. Shutting down production in an industrial plant to carry out an unexpected repair could have serious consequences, so industries have changed their maintenance model of corrective to preventive maintenance.

The application of predictive models leads to the need to perform inspections on a regular basis. These changes in the models led to the emergence of companies dedicated exclusively to the provision of this kind of services, pressing for solutions that reduce costs, time and increase safety in the course of operations. The use of robots to perform inspection and maintenance tasks become indispensable with the increasing complexity of structures and equipment to inspect and maintain. Robots with different capacities are widely used from food to the oil industry making sure that everything runs smoothly.

1.2 Inspection and maintenance conventional methods limitations

Until the widespread use of robots to perform some inspection and maintenance tasks were used conventional methods. Conventional methods tend to put man at the center of the inspection as can be seen in Figure 2. Due to the nature of the places to inspect the human presence can be dangerous or even impossible. The main limitations of conventional methods are in performing the tasks in:

- Tight spaces.
- Heights.
- Hazardous environments.

Tight spaces

In industrial facilities not all components or sensitive points that need to be inspected are in accessible locations. There are places that due to their dimensions are impossible to reach by a human. In this context, equipments like endoscopes and thermo-graphic cameras were developed to make inspection in tight places. These tools are expensive and require skilled operators, yet in some cases it is not possible to use them. Disassemble part of the equipment is another conventional way of performing an inspection. This method involves stopping the production, pay for the man-hours of work and run the risk of damage the equipment during the process. The requisites for inspect tight spaces are then a small and simple tool to use with high autonomy and versatility.

Heights

Perform inspection and maintenance tasks at heights is another challenge. The main problem of conventional techniques is once again the presence of man on site Figure 2 . The simplest equipments used to inspect in high places are ladders, scaffolding and climbing gear, but may also be used more complex equipment such as skyjacks scissor lifters, boom lifters or cranes. The use of simple equipment involves very long operating times due to the need for mounting and repositioning and is far more risky than using a motorized solution. On the other hand the use of lifting machines implies the existence of space to move the machine. Outside all of them are susceptible to weather conditions. The conventional solutions presented are all in some way dangerous, and require qualified personnel, physically and mentally fitted for the job. The requisites for inspect at heights are then a climbing capable tool that can be used both inside and outside.

Hazardous environments

The environment around the equipment and structures in an industrial installation may dictate the impossibility of human permanence. The temperature of a particular location or equipment, the high concentration of chemicals or radiation, or the presence of water surrounding the point of inspection are just a few situations that preclude humans to perform inspection or maintenance work on these sites. To allow the presence of man in these environments were developed specific equipments for each type of hazard. Typically these equipments are clothes, more specifically closed suits. The suit acts as a barrier between man and the hazard, along with other equipment such as oxygen bottles and acclimatization helps to maintain the habitability conditions inside. Due to the necessary protection some suits end up having large dimensions decreased the agility of the man inside. Along with the agility loss, also the field of view and motion decreases. The work performed in hazardous environments regardless of the equipment is always risky, slow and expensive. The requisites for inspect this conditions are then a robust and tight tool prepared to face the environment according to the function that will perform.

Figure 2: Inspection work by conventional methods, where it is possible to see the difficulties and dangers involved.

1.3 The use of robots as inspection and maintenance tools

The main advantage of the robots use in inspection and maintenance work over conventional methods is to remove man presence from the center of the action.

Figure 3: Inspection Robots

Robots have a number of characteristics which makes them suitable to perform maintenance and repair work. Some of these characteristics are presented and explained below, and can be seen in Figure 3.

- Accuracy
- Repeatability
- Autonomy
- Mobility
- Speed
- Versatility
- Economic costs

Accuracy /Repeatability

The accuracy and repeatability are essential to perform inspection and maintenance work, because they are repeated periodically. In order to obtain reliable data that can be compared, inspections must always be made in the same way, hence the importance of repeatability. Precision is essential for repeatability and to perform complex tasks. The robots as machines can be programmed to perform the same task many times. Its accuracy is directly related to its design and construction. When compared to conventional methods, precision and repeatability are incomparably superior.

Autonomy

Autonomy in robots can be seen from two points of view both of great importance for inspection and maintenance tasks. The former refers to the ability to perform a particular task or tasks during a long period of time. To achieve this autonomy the robots are equipped with batteries of high capacity and energy efficient systems. Comparing again with conventional systems, the use of robots allows to perform the most demanding and time-consuming tasks. The second refers to the ability to make decisions without operator intervention, based only on data that is collected by their sensors. This capability is being developed in various fields of robotics and will certainly be used for inspection and maintenance. It will then be possible to leave scheduling and realization of inspection and maintenance tasks in charge of a robotic system without any human intervention.

Mobility

The size, the locomotion system and the fixing elements of the robot are the key characteristics of mobility. The robots can be equipped with elements that give them ability to move in any terrain or surface. For maintenance and repair work it is essential that the robot reach specific points in complex surfaces with several obstacles. The ability to climb and navigate in vertical surfaces and overcome obstacles autonomously , enables the robot to reach high points of the structures, and perform the tasks which by conventional methods would be very difficult, risky and sometimes even impossible to do. There are several locomotion systems and the choice among them depends on the structure type and tasks to perform. The robot weight is another important factor with respect to mobility. Lightweight robots tend to be more agile and in the case of climbing robots allows to achieve higher load capacities.

Speed

Time is a precious commodity so it has to be well used. The autonomy and maneuverability that can be achieved with a robot allows it to move quickly not being always necessary manual reposition between inspection points. As the use of robots does not involve large apparatus is so often possible to perform an inspection or a small maintenance work without having to stop production or shut down devices. To operate the robot few people are necessary what makes possible to perform tasks out of normal work time without major costs. Inspection and maintenance work with robots is usually more discreet and faster than the same work done conventionally. It involves fewer people less preparation and fewer resources.

Versatility

The number of inspection and maintenance tasks performed in an industrial plant can be so large and varied that having a robot for each task is beyond expensive it is also impractical. The versatility comes from the possibility of equip the robot with different tools and program it to a large number of tasks. Inspection and maintenance work can thus be made using a small number of robots, and consequently a small team of technicians. The versatility of the robotic equipment allows its use in various conditions. For example the weather and the time of day not necessarily prevent the realization of inspection and maintenance work.

Economic costs

Specialized robots are always expensive equipment, regardless of the task they will perform. In addition to its initial price there is a need to train operators and perform maintenance on the own robot. However, the investment is easily recovered due to the increase in productivity and reduction of personnel and security costs.

1.4 The use of climbing robots as inspection tools

Climbing Robots like those in Figure 4 are robots with the characteristics described above that are able to move on vertical surfaces. In this document is given particular attention to this capability because it is one of the main capabilities of Omniclimber as its name indicates. There are several different ways to enable a robot to climb a vertical surface, ahead are presented and described the main ways used to do it. The ability to climb is one if not the greatest advantage over the use of conventional methods. Operations performed at heights in a conventional manner are always risky, even when proper equipment is used.

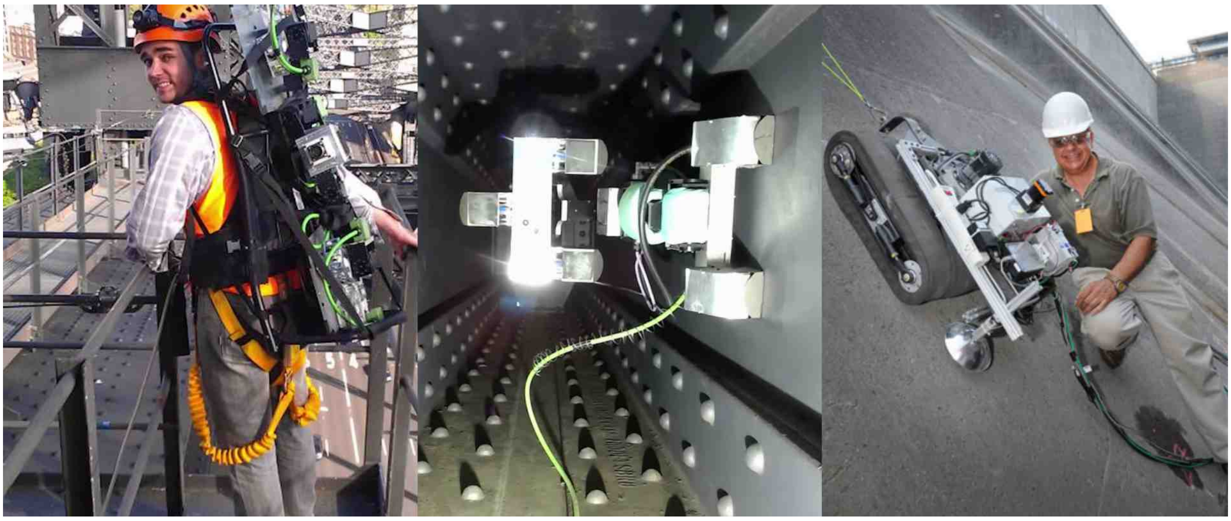


Figure 4: On the left and center is the bridge inspector climbing robot "Croc", at the right is the "Robotic crawler" from the International Climbing Machines of Ithaca

The main reason driving the development of robotic solutions for inspection is the exponential growth of the market, caused by the increasing legal requirements of safety and alterations in maintenance models by a growing number of companies.

1.5 Goals for this research work

The work presented here focuses on the development of an inspection climbing robot able to climb and navigate over ferromagnetic structures. This type of structure is present almost everywhere in industry so there is always demand for new solutions. Gas and oil tanks, wind turbines, pipelines and vessels, are just a few examples of ferromagnetic structures. All these examples have in common the need to be inspected, maintained or painted regularly with serious consequences if it does not happen, which reinforces the constant demand for new equipment increasingly capable and technologically advanced. There are several robots developed on the same objectives of Omniclimber, and even this already have versions from previous work, however there is always lot of space for improvements on many aspects of climbing robots. This work has three main objectives:

- Reduce the weight of Omniclimber in general.
- Conceptual and detailed design, prototyping and testing of a new transition mechanism.
- Apply effectively to Omniclimber Switchable Magnets in place of the electromagnets.

In addition to these objectives, the robot must remain able to meet the original objectives, which are:

- Be able to climb and navigate over ferromagnetic structures;
- Possess high speed and maneuverability, in order to reach to any point on the structure rapidly and scan the whole structure's surface;
- Be able to adapt to both flat and curved structures;
- Be low cost and easily reparable;
- Be simple and modular;

In this study is also made the dynamics and structural analysis of the implemented mechanisms, its detailed design, implementation and testing.

2 STATE-OF-THE-ART ON CLIMBING ROBOTS

The term "climbing robot" in literature can define two types of robots. The first type are robots with the ability to move in rough terrain, like rock climbing robots [2], the second type are robots that have the ability to move along a surface regardless of its orientation relative to the ground, without leaving it [3].

Figure 5: Inspection Climbing Robots on different types of structures.

In this work, when the term "climbing robot" is used it refers to the second type. Climbing robots have several uses, we can find them in many different areas making the most varied jobs as shown in Figure 5. Its application is mainly related to security and costs, so happens when or is too dangerous, or too expensive to put a human.

The development of these robots is made for specific tasks in areas such as inspection, maintenance, cleaning and diagnosis in hazardous environments, outside of tall buildings and other human made structures. Over the last decades have been developed a considerable number of climbing robots. Some of them are presented according to the task for which they were developed:

- **Inspection:** inspection of nuclear plants [4], pipelines [5], construction [6], wind turbines [7], oil tanks [8], tubular structures [9] and quality control of welds [10].
- **Cleaning:** glass facades cleaner [11].
- **Construction:** truss positioning [12], and naval construction [13].
- **Maintenance:** remote maintenance applications in hazardous environments [14], maintenance and dismantling tasks in nuclear facilities [15] .
- **Surveillance:** surveillance of persons and property through the positioning at high points [16], [17].
- **Transport:** large payload capability robot to lift tools and material [18].

2.1 Climbing Robots Locomotion

The simplest way to categorize the climbing robots according to its mode of locomotion is to divide them into three groups:

- Wheel based climbing robots
- Sliding Segments climbing robots
- Multi-legged based climbing robots

Wheel based climbing robots

There are three types of wheel based robots, as can be seen in Figure 6. Those who use the wheels as wheels, those which use wheels as wheels and legs, called "Whegs" and the last who use caterpillars instead of wheels.

Normal wheel based robots are simple, fast and allow continuous movement. The main disadvantage is the low maneuverability, resulting from the distance between the robot and the surface when passing over an obstacle. Adhesion systems by suction or magnetic are sensitive to this distance and fail when it increases.

Whegs are a combination of wheels and legs, bringing together the advantages of both. The use of this type of locomotion mechanism improve the holding force because there is always an adherent surface in full contact with the surface. It is possible to use various adhesion systems, even those in the normal wheeled robots makes them less maneuverable. The main disadvantage is that it is not possible to perform homogeneous movements using whegs due to bumps between two legs.

The development of robots with caterpillars has been made to overcome the problems related to the obstacles and defects in surfaces, which existed in the normal wheel based robots. This type of robots has an excellent behavior at all levels on flat surfaces but presents difficulties in curved surfaces of small diameters.

Figure 6: Wheel based climbing robots, from left to right: Wheg, Wheel and Caterppilar base Robots.

Sliding Segments climbing robots

Sliding segments climbing robots are simple robots that use legs with only one degree of freedom to move. The legs only move forward and backward alternately, remaining half fixed to the surface while the other half moves. The robots with this kind of movement can be used in various environment and structures. They admit the use of all types of adhesion system giving them the adaptability cited above.

There are three different types of sliding segments robots. Those who have multiple legs with small feet (SDL), those which have two legs and big feet (SDB) and the snake type robots (SC).

The sliding segments with multiple legs use relatively weak adhesion systems because they have a larger number of support points. This allows them to overcome obstacles easily. Despite the high number of legs the control of such robots is not as complex as in the multi-legged robots, because the legs only perform simple movements of only one degree of freedom.

With just two legs and big feet, Biped or inchworm robots use strong adhesion systems to move. With these robots it is possible to overcome great obstacles and to move from one surface to another nearby.

Snake type climbing robots are mainly used in terrain exploration, but it has already been successfully tested on pipes as shown in Figure 7 by the robot HyDRAS-Ascent from (RoMeLa). Their way of functioning is applying continuous contact, wrapping themselves around the tubular structure or expanding against the interior walls.

Figure 7: Robotics and Mechanisms Laboratory (RoMeLa) of the College of Engineering at Virginia Tech serpentine robot "HyDRAS-Ascent"

Multi-legged base climbing robots like that in Figure 8 are complex devices. The displacement is achieved by the synchronized movement of the legs, which have at their tops the adhesion mechanisms. The number of legs varies between a pair up to eight legs in most complex robots. The adhesion is achieved by using suction [19] or magnetic [20] systems like the others, however the problems recorded in the two previous types do not occur. A major advantage of these systems is to remain stuck to the surfaces even when one or more legs is compromised. This advantage comes from the fact that each leg has its own adherence system. The mobility achieved is good, and the bond strength to surfaces is high. The disadvantages presented are the low speed and the complexity of the control system.

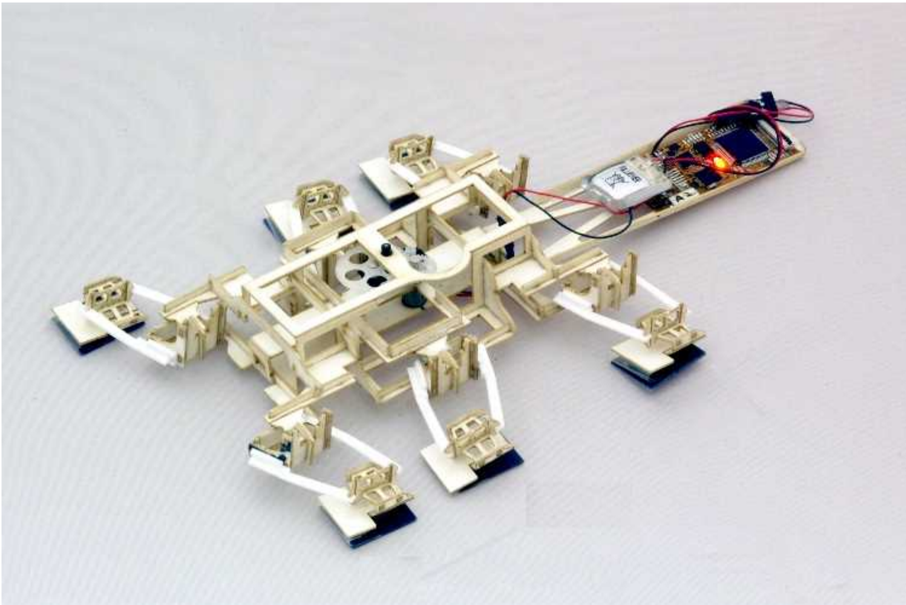


Figure 8: Multi-legged base climbing robot from UC Berkeley Biomimetic Millisystems Lab

In conclusion the various types of locomotion for climbing robots can be classified building on three criteria. The criteria used are mobility, speed and complexity.

In terms of mobility the Biped robots are the best. These robots have good mobility on any surface and allow moving from one structure to another that is within reach. In terms of speed the best ones are wheel based robots. Its simplicity allows them to move easily and quickly along the structures. Simplicity is another important feature and once again the robots who earn this aspect are the wheel based robots. Without legs or differentiated segments its construction and control are very simplified.

Climbing Robots Challenges

Two of the most important abilities that makes a climbing robot more appropriate for industrial applications are the ability to overcome obstacles in its path, and the ability to transit between perpendicular planes. This is important since most of the complex industrial installations include surfaces with some sort of obstacles, such as ridges, flanges and gaps. When these obstacles are unsurpassed, the robot should be able to find a way to go around, which most of the time involves plane transitions.

Even if none of the above obstacles are present on the structure, just the ability of the robot to move on the ground and then transit to a vertical surface and vice versa increases its autonomy. Some climbing robots have used innovative features to solve some of these problems. Strategies adopted include:

- Use of relative scale, by employing very small robots when compared with the size of the obstacle, so the robot can navigate on the obstacle like it normally navigates on the surface [21]. This is for instance true in the Magnebike: a compact magnetic wheeled inspection robot [22]. This robot benefits from small magnetic wheels and is designed to work on narrow surfaces and tight spaces. It uses a wheel lifting mechanism for overcoming obstacles and performing plane transitions.

- Using linear effectors and legs to overcome the obstacle [23], relying on obstacles and surface features of a specific size.

- Using complex hybrid locomotion mechanisms which combine the principles of wheels and legs (walking wheels concept)[24].

- Using multi-robot collaboration to connect multiple units and transpose obstacles together[25]. The AliciaIII is a single robot composed of three separate modules which are connected through links[26]. Each module has an adhesion device based on suction and wheels for locomotion. The advantage of this articulated design is that it allows to overcome small obstacles such as gaps or ridges on the walls, by detaching one of the modules at a time and moving it over the obstacle. Even plane transition is not reported with AliciaIII, but this concept should also allow the robot to perform plane transitions. However this results in very high torque demands on the joints due to the relatively heavy climbing modules (4 kg each module) and the long arms.

However, most service robots are too large to use their relative scale as an advantage to help them overcoming the obstacles in their environment. Use of multi-legged robots or hybrid locomotion for climbing purposes requires greater number of degrees of freedom (DOFs), without necessarily improving the ability of robots to progress in a complex workspace. Using multi-robot collaboration suggests a complex operation and control scenario which is not desirable for industrial applications that demand for simple and reliable solutions. Multi DOF arms usually offer good maneuvering over 3D structures. The arm can be serial [27][28][29], parallel [30] or hybrid [31]. However, these robots are generally heavy, big and complex. To be able to pass bends, these robots employ at least four DOF [29][31][32] and usually have a mass of more than 20 kg. Due to such problems, these robots could not find their way out of the laboratories.

2.2 Climbing Robots adhesion system

Locomotion and adherence are the most important functions in a climbing robot, so they receive special attention during the development of such robots.

The most common forms of locomotion have already been discussed, so now will be addressed the forms of adherence. Each form of adherence can be understood as a system. Systems that generate the forces responsible for keeping the robots stuck to the surfaces. The main adhesion systems used in climbing robots are then:

- Magnetism (Magnetic force)
- Vacuum (Suction force)
- Gripping (Mechanical force)
- Dry Adhesives (Chemical force)
- Electrostatic (Electrostatic force)

Magnetism

Magnetism or use of magnetic force to provide adherence is common on climbing robots. Despite being limited to ferromagnetic structures the high number of such structures especially in industrial facilities and equipment, promotes its use.

There are two ways to produce the magnetic forces, using permanent magnets or electromagnets. Both forms have advantages and disadvantages.

Electromagnets can be controlled. The magnetic field can be switched on and off and even intensified and decreased, all depending on the characteristics of electricity supplied to them. This characteristic has a lot of relevance in robotic uses, because it allows to adapt the intensity of the magnetic field to the surface and work. On the other hand these devices are heavy and will only operate if they have a source of electricity. A power failure corresponds to the detachment of the magnets and the robot fall. The electrical connection of the electromagnets precludes its use in mobile parts such as the wheels.

The disadvantages of electromagnets and the increased availability of permanent magnets made of stronger alloys like NdFeB-alloy makes them the most widely used solution. Permanent magnets are stronger, lighter and easier to integrate than electromagnets, but unlike the electromagnets is not possible to control their strength directly. Indirectly it is possible varying the distance between the magnet to the surface, or composing devices with more than one permanent magnet called switchable magnets. Switchable magnets are devices first designed for attaching metal parts to be machined in metalworking industry. A switchable magnet consist in a metal body with two permanent magnets inside, changing the position of the poles of the magnets rotating a lever the magnetic flux varies through the body as well as the magnetic force generated. These devices enable the control of magnetic force without the drawbacks of electromagnets. The used Switchable magnets have already been successfully applied in robotic applications like Cy-mag3D [33] in Figure 9.

Figure 9: Cy-mag3D: Miniature climbing robot from Laboratoire de Systemes Robotiques (LSRO), Mobots group, Ecole Polytechnique Federale de Lausanne (EPFL)

Suction

The generation of vacuum is the most widely used form of adhesion in climbing robots [34]. The use of vacuum consists of removing air between the surface and the cup. The negative pressure inside the cup maintain the robot stuck to the surface. It can be done actively using suction pumps or passively like Dexter robot shown on Figure 10 which generates vacuum by pressing the suction cups against the surface forcing air out like. The obtained forces can be very high and therefore these systems support heavy loads, however not all surfaces allow its use. The surfaces must be smooth enough to allow the suction cups to close the gap between its perimeter and the surface in order to create vacuum. This problem extends to the existence of obstacles and small flaws on surfaces. In addition to the problems cited above, to generate vacuum actively, it is necessary to consume energy, which results in a loss of autonomy of the robot.

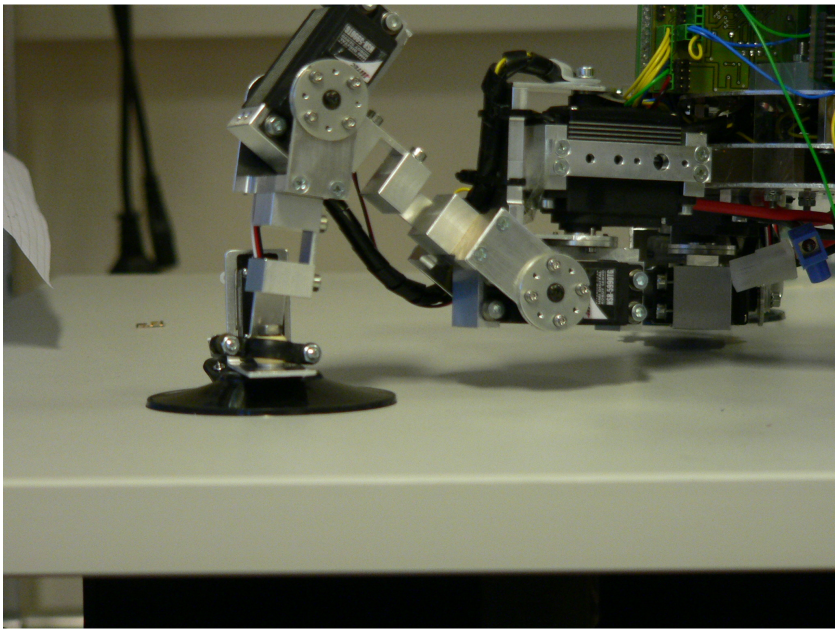


Figure 10: Climbing robot Dexter which adheres to the wall by passive suction cups from University of Osnabrck Smart Embedded Systems Group

Gripping

Gripping is to simply use a claw or a similar system to embrace surfaces to climb. This form of adhesion is the most suitable to take advantage of the shape of the structure, commonly used for robots that climb thin tubes and others structures easy to grasp. Robots like ROMA 1 [32] and 3D Climber [35], shown in Figure 11, are examples of robots that use grippers, for traveling in complex metallic-based environment.

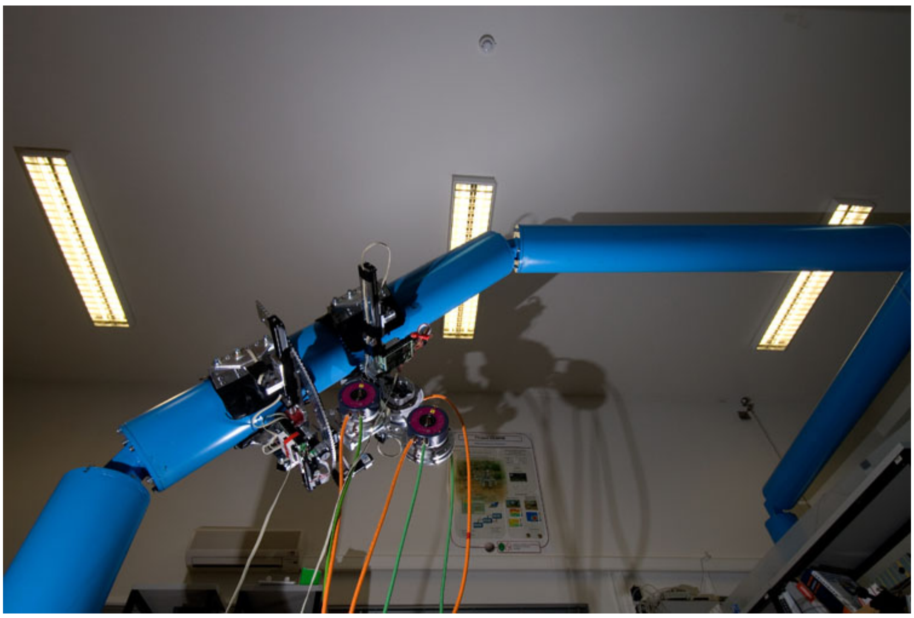


Figure 11: 3D CLIMBER Pole Climbing Robot from ISR Embedded Systems Lab University of Coimbra

Dry Adhesives

The use of dry adhesives as a mean of obtaining adherence to the surface has also been explored in the field of climbing robots. Dry adhesive materials are made up of millions of tiny filaments, observable only under the microscope. When in contact with a surface these little filaments penetrate any roughness presented and creates millions of contact points even on surfaces that look smooth. Beyond the pure physical contact, due to the very small scale of the filaments also are felt electrostatic effects and van-der-Waals-forces. The study of this type of adhesive was made by scientists from the Stanford Research Institute (SRI) and Carnegie Mellon University (CMU), inspired by the fingers of geckos, that are reptiles capable of climb any surface, even the smoothest, such as glass. Robots such StickyBot [36] in the Figure 12 and WaalBot [37] are examples of climbing robots that use this type of adhesion system.

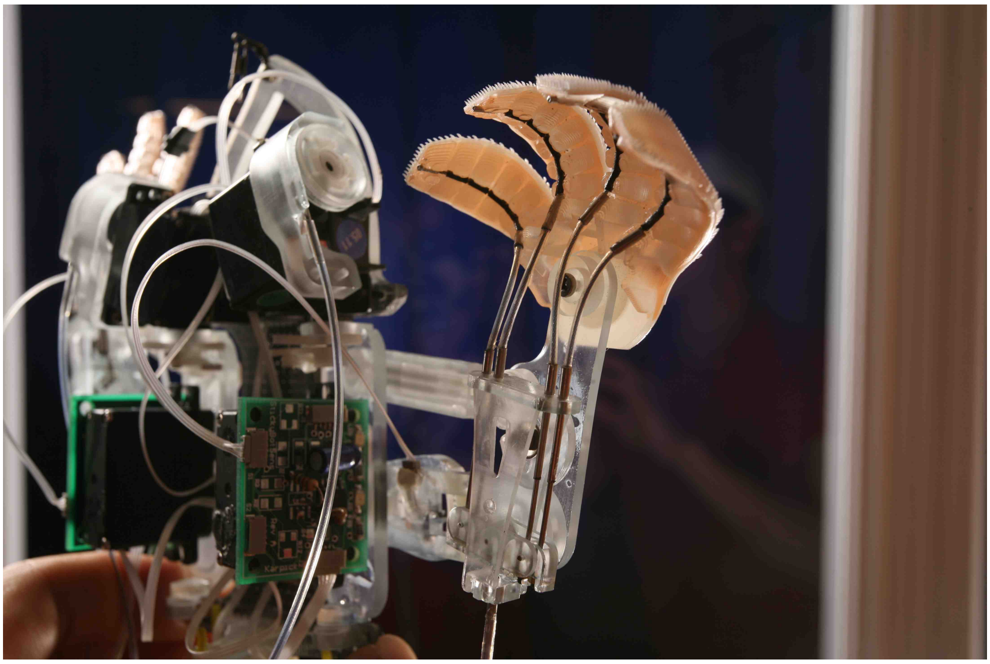


Figure 12: "Stickybot" Bio-inspired gecko robot from Stanford University and MIT

Electrostatic

Of all adhesion forms presented the use of electrostatic is the latest and the less studied yet. This principle was investigated with detail at Stanford Research Institute (SRI) [38] and implemented in the structure of a robot shown on Figure 13 moving on caterpillars . This technology has demonstrated good results and is considered promising. The forces generated are reasonable for the mass of the system and its power consumption is reduced.

Figure 13: SRI International wall-climbing robot using a new electrical adhesive technology called compliant electroadhesion.

3 OMNICLIMBER

The OmniClimber is an omnidirectional climbing robot for inspection of ferromagnetic structures which is capable of navigating on both flat and curved surfaces with good maneuverability, thanks to its passive curvature adaptation mechanism, its magnetic adhesion mechanisms and through the use of three custom made magnetic omnidirectional wheels [39]. Taking advantage of its magnetic omnidirectional wheels, the holonomic drive robot can move in any direction on vertical surfaces without requiring to change its yaw angle.

In order to be able to transit between planes and overcome obstacles, we decided to integrate an articulated arm with a magnetic adhesion unit as its end effector. Through this hybrid system, we combined the advantages of a wheel based climbing robot (speed and simplicity), with the advantages of the articulated climbing robots (maneuverability in 3D structures). The characteristics of the last version of the OmniClimber are stated in Table 1.

Table 1: OmniClimber characteristics

Diameter x height Mass	197 x 84 mm 1110 g (without transition system)
Articulated arm weight	610 g
Actuation	3 Dynamixel MX-64 rotary actuators
Mechatronics and control	Stand-alone robotic system with integrated control board on the chassis and IR module
Power	Onboard LiPo 1000 mAh battery
Wheels	3 Omnidirectional Magnetic Wheels 70mm diam.
Min adhesion force*	25,5 N (chassis electro-magnet *off*) 45,0 N (chassis electro-magnet *on*)
Max climbing speed	14 cm/s
Total weight of the Robot	1720 g
Max payload*	1200 g
Movement	Full omnidirectional

*measured on a 1mm thick sheet of steel

The transition mechanism from the previous version, shown in Figure 14, had several novelties like the use of only one actuator to control two joints at different speeds and time intervals.

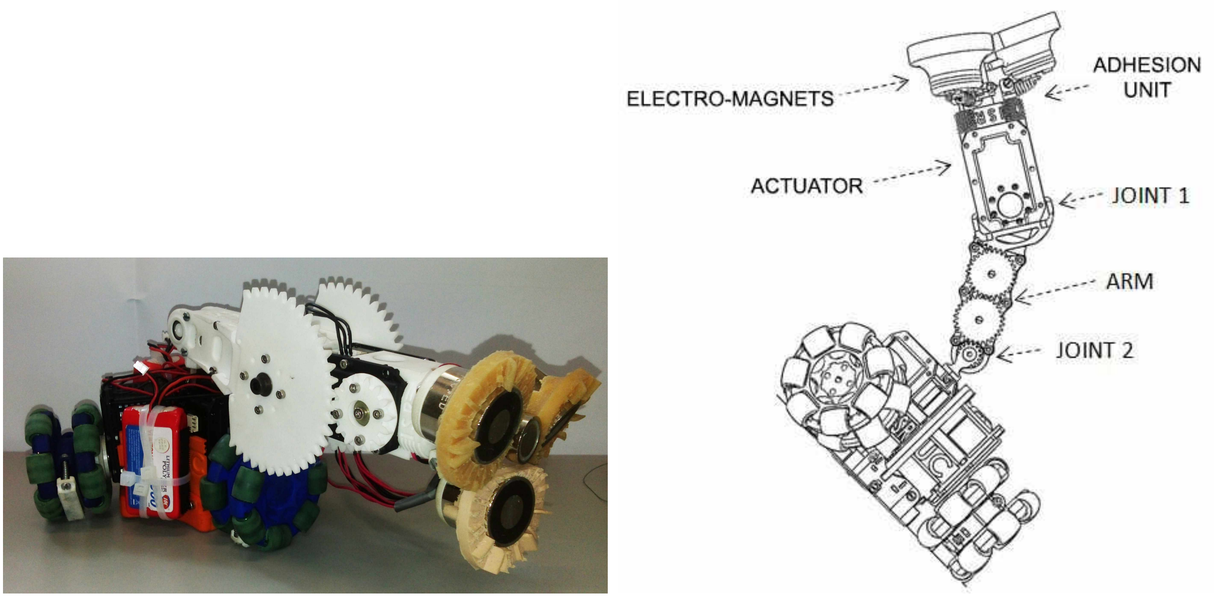


Figure 14: Previous version of Omniclimber transition mechanism[1].

The first joint, which connects both motor and arm link, rotates 90 degrees to perform the whole plane passing. Meanwhile, and with a time gap to avoid collisions between the robot and the planar surfaces, the second joint, which connects the arm link to the robot, rotates full 180 degrees, thanks to the geared transmission to the first joint, as shown in Figure 15.

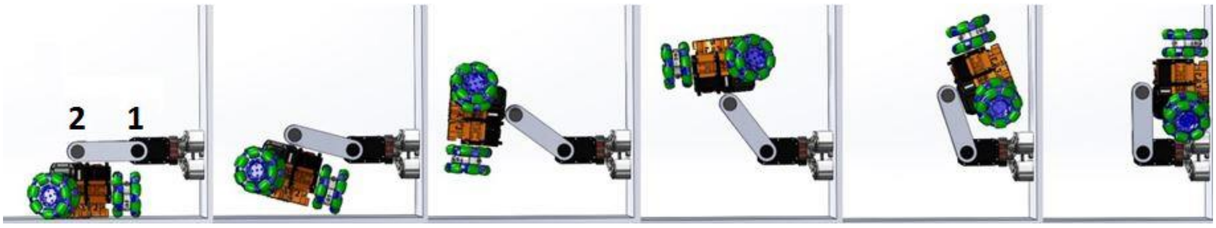


Figure 15: Plane transition routine frames.

However, and despite using only one actuator, the transmission and hardware needed for such a complex design made the whole arm too heavy for a small climbing robot such as the OmniClimber. Also, since it relied on electromagnets, it needed an extra lithium polymer battery to power them, thus increasing even more the total weight of this solution. So in the new version of the OmniClimber we proposed a novel transition mechanism with integrated switchable magnets which is lighter and has adhesion force control capabilities.

4 OMNICLIMBER NEW VERSION

4.1 Switchable Magnets integration

A switchable magnet is a system which uses moving permanent magnets to change the magnetic flux path to the inside or outside of the device, thus enabling to virtually turn *on* or *off* the magnetic attraction force of the whole system. While there are many industrial products using this technology, only a few robots employ it. One commercially available switchable magnet used in metal workshops to hold metal pieces is the MagJig 95, shown in Figure 16. This unit was the starting point for the development of a switchable magnet for climbing robot applications made in previous works [40]. It consisted on a circular 20 mm fixed permanent magnet below one circular 20 mm moving magnet. Both magnets are inside an iron housing. The device possesses an handle coupled to its top to allow the user to manually rotate the moving magnet. Total height of the magnets housing is 22 mm, while its section is 28 mm by 21 mm.

Figure 16: Magjig 95, with the magnets housing dimensions.

The goal was to modify this design to reach a better holding force per unit of mass and a better geometry for the climbing robots applications. For the adhesion unit of a climbing robot, a low profile (low height) mechanism is preferred since it results in a smaller detachment torque. It was decided to maintain the magnets diameter, since a high contact surface is important for good adhesion, while reducing the magnets height, which is more appropriate for climbing applications due to lower detaching torque, as can be seen in Figure 17.

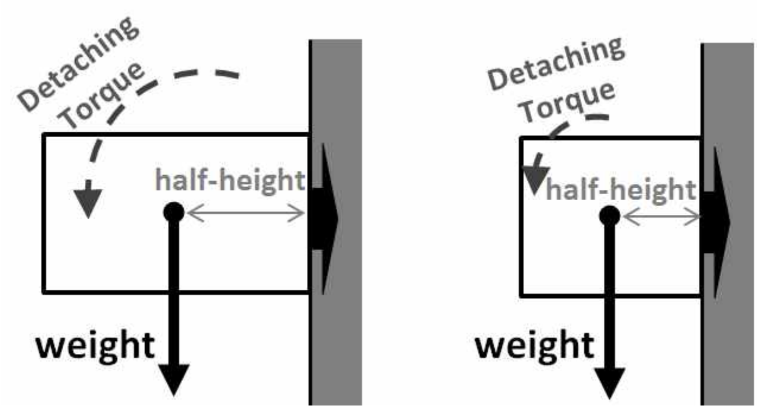


Figure 17: Torque resulting from different shapes of the device: the closest the center mass is to the surface, the less the detaching torque.

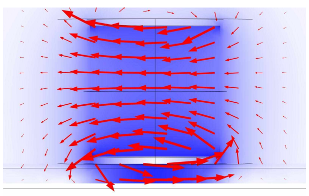
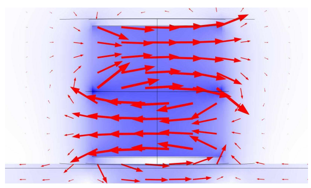
The first step in the design of new devices was to test the version commercially available MagJig 95 magnets in *Comsol Multiphysics 4.3* [41], a finite element analysis solver package for various physics and engineering applications, to observe the magnetic flux in the magnets, the housing and the object in both states of *on* and *off* and estimate the magnetic attraction force. Then it was tested the real unit and compared the results obtained with the ones from the simulations, to validate the simulation parameters.

In order to find out the effect of different design aspects and materials on the performance of the switchable magnet, it was proposed a series of modifications to the original design and simulated the flux and the adhesion force. The evaluated aspects include:

- Housing material;
- Housing shape;
- Housing diameter;

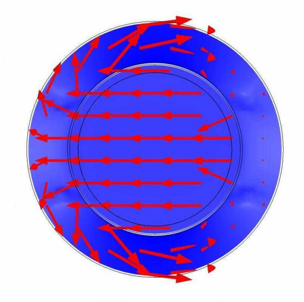
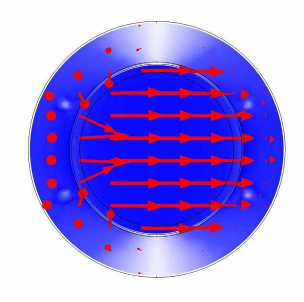
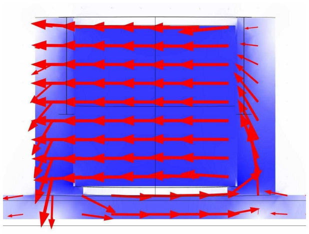
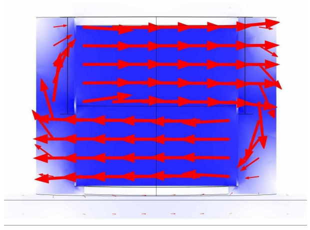
Results show that this solution is far from being optimal, with a reduced holding force of 59.3 N (Table 2). This was explained by the lack of a conductive core to direct and concentrate the magnetic flux, clearly visible on the representations of the flux path.

Table 2: Simulation results for a plastic magnet housing, showing the magnetic flux path on section view and the holding force calculated below.

Device *on*	Device *off*
	

The original housing of the *MagJig* 95 unit, includes two flat cuts at two sides. To understand the effect to the attraction force of these flat cuts, were made simulations with a steel circular housing, without the flat cuts.

Table 3: Simulation of a circular magnet housing, showing the magnetic flux path on both top and section view, and the holding force calculated below.

Device *on*	Device *off*
	
	
81.6 N	0.5 N

As can be seen in Table 3, the holding force is much smaller when the device is on (81.6 N vs 338.4 N). This shows that without the flat cuts at the two sides of the housing, a significant amount of magnetic flux passes through the housing, and thus the flux passes through the ferromagnetic object that should be grasped. The explanation was that when the SM is on (magnet poles aligned), the magnetic flux should not be closed between the two permanent magnets. Instead, the flux should go to the surface where the magnet is attached to. A fully cylindrical housing provides a way for the flux to go around the housing axis, from one magnetic pole to the other, thus not forcing the flux to pass through the bottom surface resulting in a significant reduction of the adhesion force. Therefore the shape of the housing, specially the effect of the flat cuts on the adhesion force, is very important.

In order to study the effect of the diameter of the chamber, were simulated a slightly bigger chamber (Ø32 mm), and compared the results with the original device (Ø30 mm). As can be seen on Table 4, despite the increase of the holding force with an increase in the chamber diameter, however the device with Ø30 mm have the best Force/Mass ratio.

Table 4: Effect of housing diameter on holding force

Housing diameter [mm]	Total mass [g]	Holding force [N]	Force/Mass ratio [N/g]
28	79.6	289.4	3.64
30	87.7	338.4	3.86
32	95.7	364.9	3.81

Table 5: Magnetic force for different magnets diameters, for novel device.

Diameter [mm]	Force [N]
18	162.2
20	180.0
22	183.4

From the results presented in Table 5, it is possible to conclude that the (Ø20)mm magnet despite not having the greatest adhesion force is the most balanced solution offering a great ratio force/size. Therefore the new housing dimensions are (Ø28x12) compared to (Ø30x22) of the original unit. The housing's material is AISI 1018, the same from *MagJig*'s housing. The new switchable magnet developed for climbing robot applications is depicted in Figure 18.

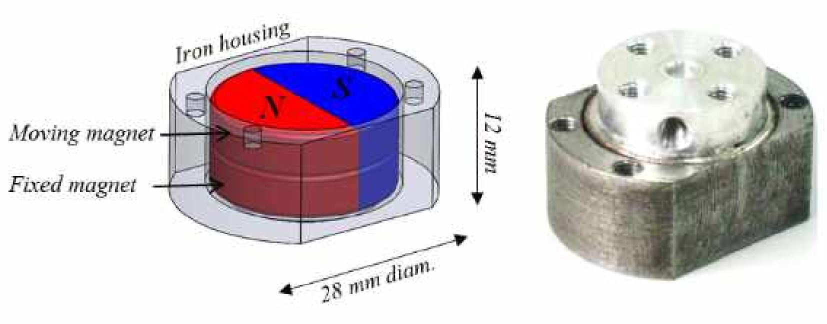


Figure 18: Novel switchable magnet developed for climbing robot applications

The device was tested in two steel plates with 1 mm and 3 mm thick and then the adhesion force of the new unit was compared with the one from MagJig 95. *MagJig* 95.

Table 6: Comparison between the *MagJig* 95 and the novel device

	MagJig 95	Novel device	Variation
Mass [g]	87.7	42.1	-52%
1 mm steel:			
Holding force [N]	112.6	100.1	-11%
Force/Mass ratio [N/g]	1.28	2.38	+85%
3 mm steel:			
Holding force [N]	338.4	183.4	-46%
Force/Mass ratio [N/g]	3.86	4.36	+13%
Detaching torque [N.m]	0.094	0.025	-73%

As can be seen in Table 6, for both cases of $1mm$ steel and $3mm$ steel, the adhesion force/mass ratio is improved comparing to the *MagJig* 95. In case of the $1mm$ steel, this ratio was increased 85%, while for the $3mm$ steel, the increase was 13%. This is mainly due to the fact that in thin plates, most of the large magnetic field of the *MagJig* 95 is not used, while the magnetic field on the novel device is much more focused on the region closer to the surface of the plate, thus is used more efficiently. This effect is depicted in Figure 19. Furthermore, there is a significant reduction of the detaching torque of 73%.

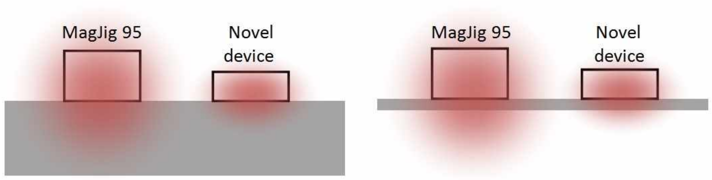


Figure 19: Comparison between the magnetic field of the MagJig 95 and of the novel device in plates with different thickness

Central Magnet

The central magnet shown in Figure 20 is the only SM present in the robot body. Together with the permanent magnets of the wheels ensure the adhesion strength for most of the time. The advantage of using a Switchable Magnet in the center of the robot is the ability to adapt the adhesion strength to the surface conditions.

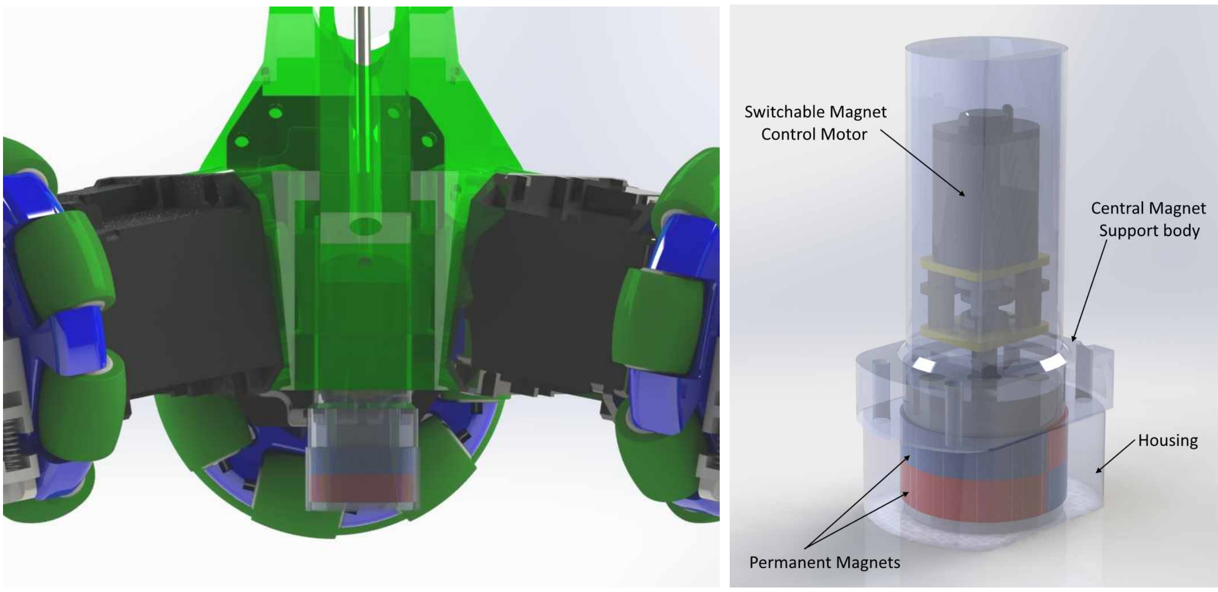


Figure 20: Central magnet holder and inside components

The ability to control and adjust the magnetic force generated by the OmniClimber's central magnet is extremely important in the following scenarios:

- When the robot is passing from one plane to the other and to facilitate detachment of the robot from the surface, one should be able to switch off the magnetic adhesion force.
- When the robot is moving the magnetic adhesion force should be inferior to when it is stationary and performing inspection or maintenance tasks, in order to reduce friction and improve the robots' dexterity and maneuverability.

- When the robot is moving upside down the magnetic adhesion force should be superior to when it is moving vertically or on top of the surface.

- When the robot moves to another structure and the surface material or thickness changes, the magnetic force generated should be adjusted to the new conditions.

One of the problems of the previous version of the OmniClimber was that in order to adjust the magnetic force, one had to manually adjust the position of the central magnet unit inside the robot chassis. This was not optimal and presented a severe limitation in all of the scenarios mentioned.

Therefore we set out to integrate a remotely controllable force adjustment mechanism, to not only turn the magnets *on* and *off*, but also to control the adhesion force. One possible method was to integrate an actuator to move the central magnet inside the chassis. To do this one has to use a rotary to linear transformation mechanism. By controlling the distance between the central permanent magnet and the surface, one could control the magnetic adhesion force. This effect can be roughly translated by the following empirical expression given by magnets manufacture HKCM [42]:

$$F_r = \frac{F_h}{1+s} \quad (1)$$

Where F_r is the Magnetic force at distance s, F_h is the Magnetic force depending on the material and s is the distance between the magnet and the surface.

One could use an electromagnet but then it would have its limitations, such as safety problems in the event of power failure.

The solution adopted was to use an actuated switchable magnet. This results in a simpler, more compact and fail-safe mechanism. This solution also has the advantage of:

- Being able to control the force, and not only to switch the magnet *on* and *off*.

- Being a non back drivable mechanism, meaning that it consumes energy to rotate one of the permanent magnets, but after reaching the desired angle position the actuators can be turned off while remaining in that same position and not consuming any energy.

Adhesion force changes based on the angle of the upper magnet relative to the lower magnet, as magnetic fields align and reorient. We set out to measure in detail this variation by first running a simulation in COMSOL of the magnetic flux and the adhesion force obtained for different angles and then by measuring the adhesion force experimentally in a prototype.

The force generated by a switchable magnet varies with the orientation of the poles of the magnets inside. The magnetic flux always occurs between opposite poles. Thus if the poles of both magnets are aligned the magnetic flow is forced down the casing through the surface material to re-enter the housing on the opposite side. When this happens, the switchable magnet generates an attractive force proportional to the alignment of magnets.

If the poles are fully aligned the generated force is maximum. If they are not aligned, strength decreases because part of the flux circulates between the two magnets instead of going down to the surface. If the poles are completely inverted, the magnetic flux flows directly between the magnets and the switchable magnet does not generate any force of attraction, as shown in Figure 21. Due to small leaks in the housing thin side there is always a residual attraction force.

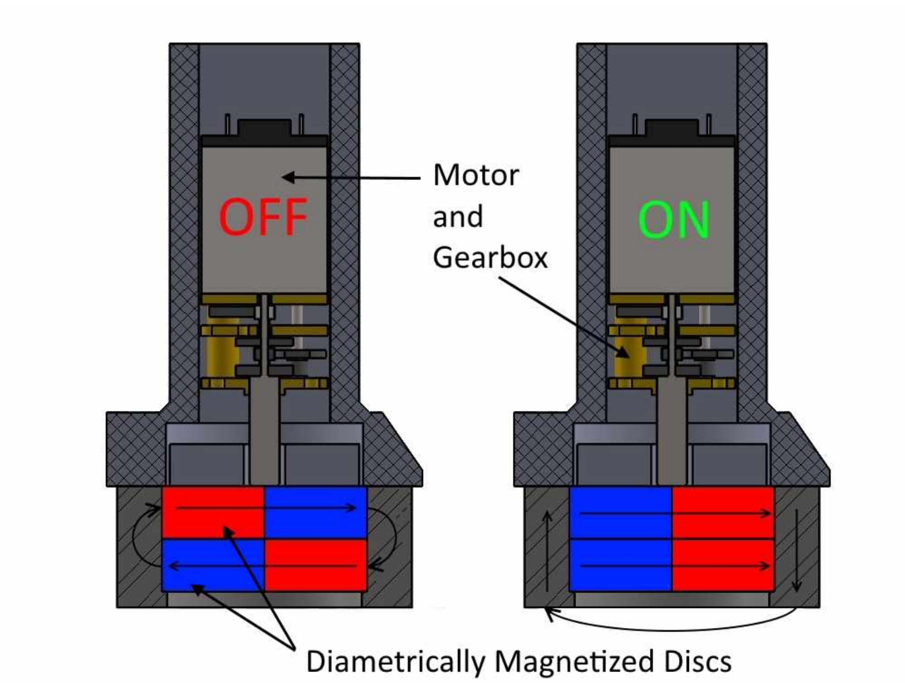


Figure 21: Magnetic flux in *on* and *off* states

Though it is possible to select and maintain a state between *on* and *off* on the switchable magnet, the magnetic forces between the two magnets force them to move to one of the those two preferential positions. So to maintain the top magnet at a desired angle, so that the mechanism is non back drivable, it is necessary to counter the torque which tries to align the upper magnet with the lower one. For this, we selected an actuator whose internal friction is big enough to stop the shaft's rotation due to the torque exerted by the two magnets. In this case we used a Pololu Micro HP with 298:1 transmission ratio.

Adhesion Unit

The Adhesion Unit is a device designed to contain two Switchable Magnet controlled simultaneously by a single motor. The transmission system was designed and developed specifically for this application. The body that supports both SMs is part of the transition mechanism and it is this device that ensures adherence during transitions.

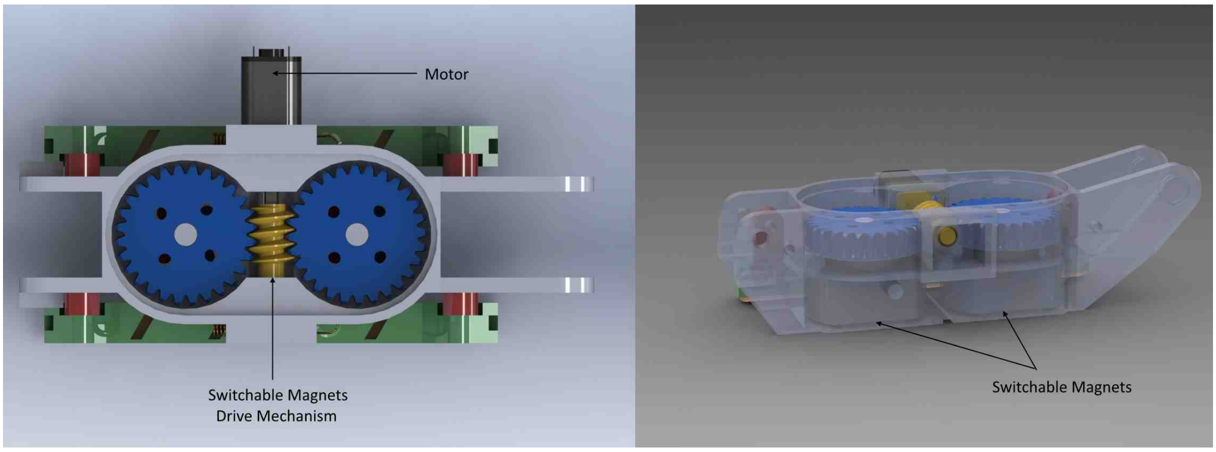


Figure 22: Adhesion Unit Worm drive Transmission

The adhesion unit of the arm should be able to support the full weight of the robot and also the detaching torque during the plane transition. This adhesion unit possesses two switchable magnets at a certain distance from each other.

As can be seen in Figure 23, d is the distance between the center of the adhesion unit and the anchor point and s is the distance between the center of switchable magnets. These distances are calculated so that the force generated by the switchable magnets of the arm adhesion unit is sufficient to support the torque generated by the weight of the robot. The other distance in the diagram of the Figure 23 is (D), which is the distance between the robot body's center of mass to the anchor point. The torque generated by the weight of the robot T_W is function of this distance and is given by:

$$T_W = D \times F_w \tag{2}$$

The maximum torque is generated for the highest value of distance (D) which is 120 mm. The torque in this situation is:

$$T_W = 0.120 \times (1.120 \times 9.81) = 1.32Nm \tag{3}$$

Where T_W is the torque generated by the weight F_w.

To support the robot weight the distance (d) must be such that the value of torque generated by the switchable magnets T_{AU} is greater than that generated by the weight of the robot:

$$T_{AU} \geq T_W \tag{4}$$

For this to happen (d) is given by:

$$d = \frac{T_{AU}}{F_{SM}} \tag{5}$$

Where $T_{AU} = T_W$ and F_{SM} is the force generated by the two switchable magnets. Therefore (d) is:

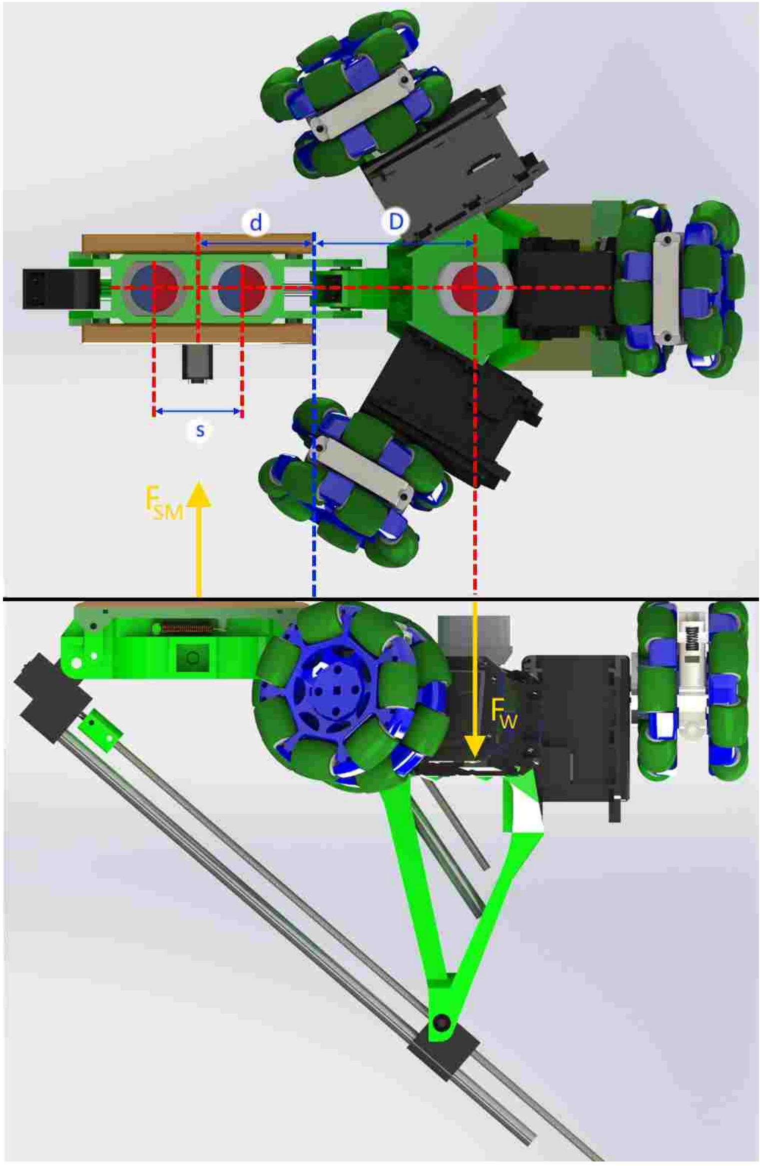


Figure 23: Distances and forces diagram

$$d = \frac{1.32}{116} = 11.4mm \tag{6}$$

The distance (d) that we chose was 20 mm for a safety factor of 1.7.

The distance (s) can be obtained by dividing the generated torque of the weight by the force of each switchable magnet:

$$s = \frac{1.32}{58} \geq 0.023m \tag{7}$$

Here we chose s=34mm in order to respect the dimensions which results in a safety factor of 1.5.

Both switchable magnets can be actuated by a single motor, through a non back-drivable worm gear mechanism. The required torque to actuate the two switchable magnets varies with proximity to a ferromagnetic surfaces.

The worst case scenario happens in the absence of any ferromagnetic surface or material. In this case each SM unit requires 0.25 Nm to turn, or 0.5 Nm in total.

Here we used a MICRO HP Pololu gear motor with a gear ratio of 100:1 which is coupled with an additional custom made worm drive transmission increasing its gear ratio 28 times providing more than 1 Nm at the output shaft considering a 50% efficiency on the worm drive transmission.

Furthermore, we integrated a mechanism, called "Skis", which is used to increase the friction between the robot and the surface, thus reducing the risk of slippage when the robot is stationary and held only by the adhesion unit on a vertical surface. In the beginning of the transition the robot is in contact with the surface with only two wheels. During our experiments we saw that at this point while the robot returns to its normal position with the three wheels in contact some slippage happens on the adhesion unit. To prevent this from happening it is necessary to create friction. The problem is that the friction hinders the movement of the robot. So the developed solution has to prevent slipping without hampering the progression of the robot on the surface. To do this the bottom side of the Skis is covered with an high friction silicon rubber.

As shown in Figure 24 when the robot is stationary the weight of the robot pushes the skies against the surface preventing it from happening. In the opposite situation, when the robot is climbing, the Skis retreat.

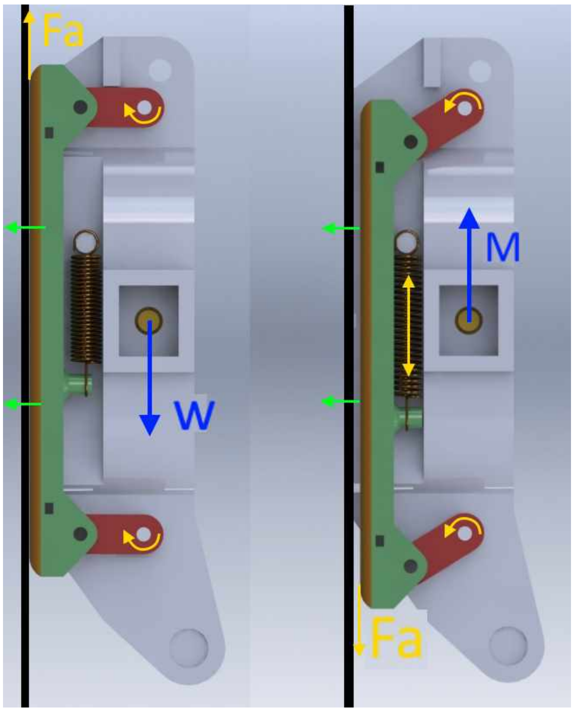


Figure 24: Anti Slip System (Fa - friction force; W - weight; M - movement force)

4.2 Transition mechanism

In this section we describe the novel parallelogram mechanism developed for plane transition.

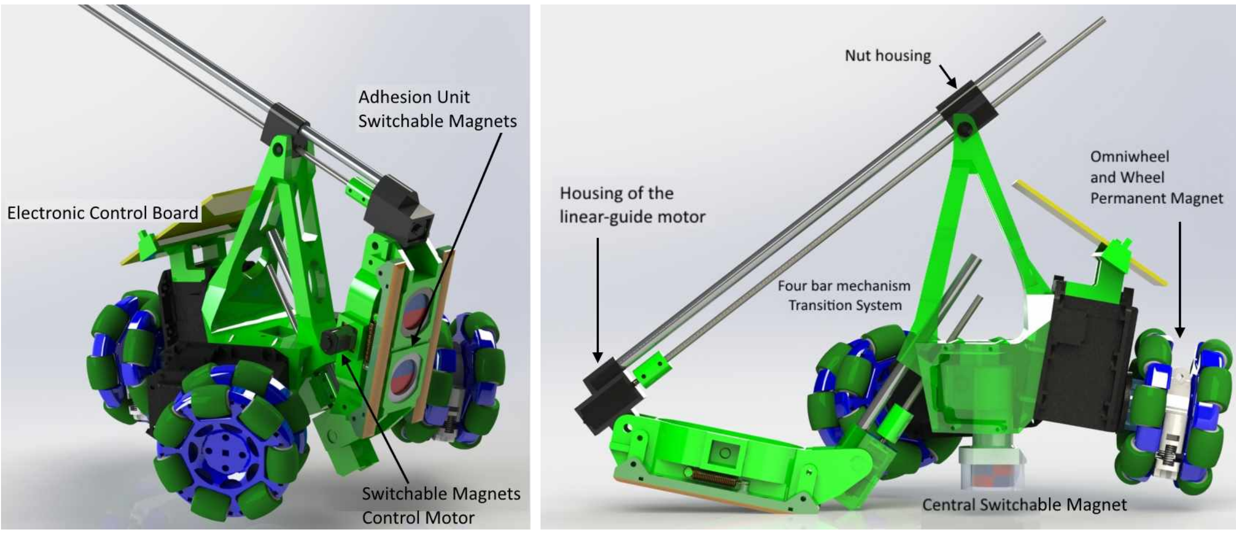


Figure 25: Omniclimber Transition Mechanism components

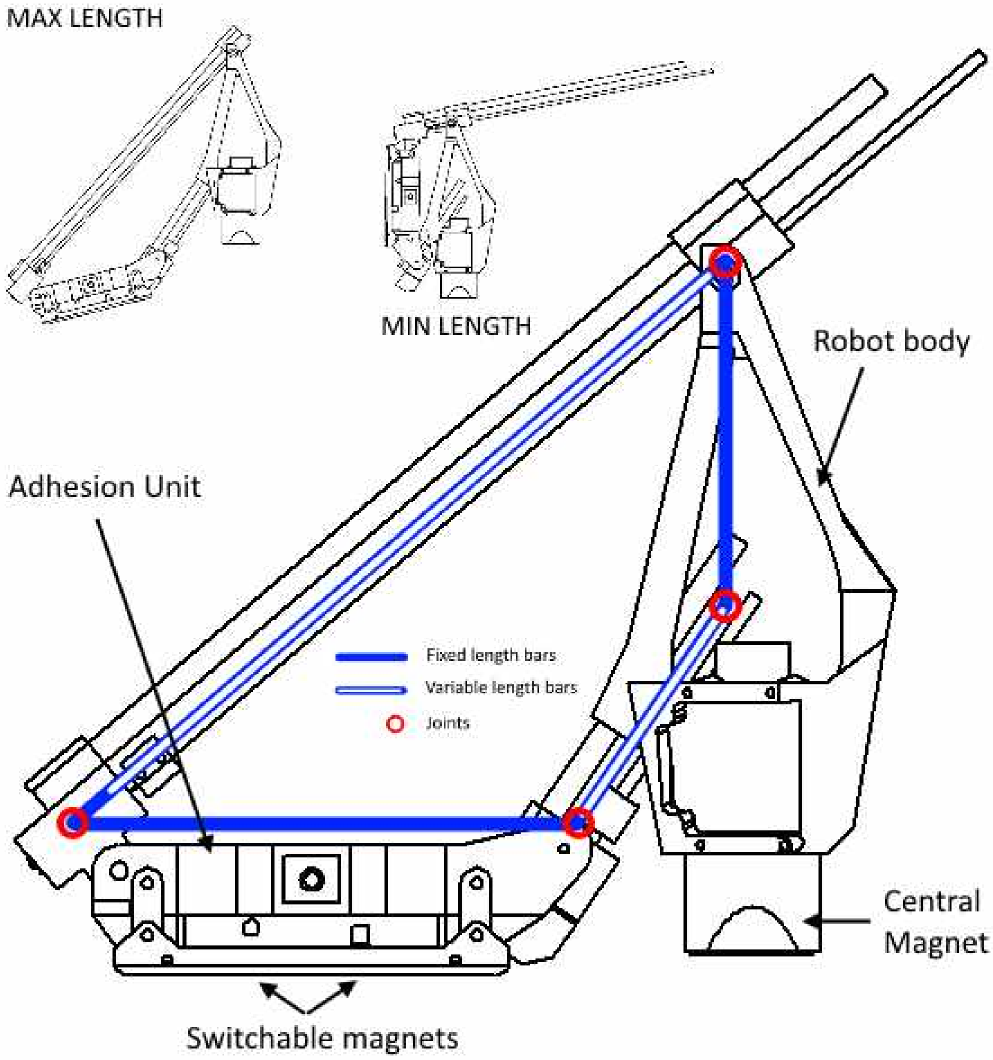


Figure 26: Transition Mechanism

The new transition mechanism shown in Figures 25 and 26 is based on a four bar system in which the length of two bars can be controlled by two actuators. The third bar is a part of the chassis and the forth bar is attached to the switchable magnet adhesion unit as can be seen in Figure 25.

By changing the length of the two variable length mechanisms, one can change the distance and angle between the two SM units of the chassis and the arm. In this way we can place each of these units on the appropriate pose during the plane transitions. To do so the two variable length bars of the 4-linkage mechanism are considered as inputs of the kinematics system.

Linear movements are created by a nut and screw system with linear guides. This solution results in a very high transformation ratio which allows the use of very small and light-weight actuators (Pololu Micro HP 100:1 gear motor, weight=9.5g) at a cost of the speed reduction (0.5 mm per rotation with the motor running at approximately 300rpm). Here the speed is less significant because plane transition does not happen very often.

Kinematics and control

Figure 27, depict the chain of the four bar mechanism. Points A and D have fixed positions and the angle between AD and CD is also fixed. The bar CD does not rotate but its length varies. Bar AB has both length variation and rotation on both vertices's. BC has also a fixed length. The inverse kinematics of the mechanisms allows us to calculate the length of the two variant length bars ((AB) and (CD)) linear guides, based on the desired pose between the two adhesion units i.e. the relative inclination between the adhesion units (90+θ) and its distance (D1), as shown in the Figure 27. The following expressions provide the lengths of the variant length bars, i.e. $l_1 = |AB|$ and $l_2 = |CD|$ based on the required inputs (d=D1 and θ)

$$l_2 = \left(\frac{D1}{\cos\varphi}\right) \tag{8}$$

$$l_1 = \sqrt{(D2)^2 + ((0.1 + CD \times \sin\varphi) + 0.1 \times \cos\theta)^2} \tag{9}$$

Where:

$$D2 = D1 + (0.1 \times \sin\theta) \tag{10}$$

and φ is a constant angle: $\varphi = 180 - 56 = 124$

Transition

Figure 28 depicts the transition process. To make the transition first the adhesion unit of the arm is placed in parallel to the new surface. Once the contact is established the SM unit of the chassis is turned off.

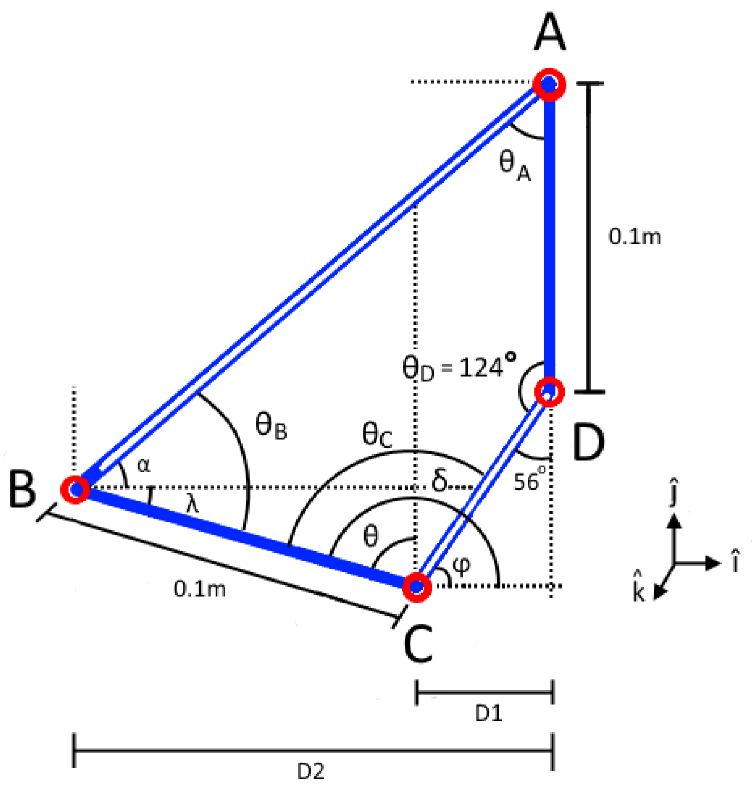


Figure 27: Transition mechanism simplification

In this case only two of the three wheels are in touch with the surface. These two wheels lift the robot. In this case the adhesion force is provided by the SM unit of the arm. But the adhesion force is adjusted to a minimum necessary adhesion force that is required to support the robot's weight and provide enough traction to the wheels for climbing. This is determined experimentally and depends on the material and the thickness of the structure. For instance for the case of this experiment which was performed on a 1mm thin steel plate, this value was around 75% of the maximum adhesion force. The robot climbs with two wheels to an extent in which it is possible to attach the third wheel. The attachment of the third wheel is performed with the help of the arm (as shown in Figure 28). In this case the SM unit of the arm provides the maximum adhesion force and acts as a safe anchor to overcome the generated torques by the weight of the robot. Afterwards the SM unit of the arm is turned off and the arm return to its original pose before the transition.

Figures 35 and 36, represent the percentage of the applied force to the maximum force of the SM units during the transitions, ground to a vertical wall and wall to the celling. The letters on the bottom axis represent the frames shown on Figures 33.

Torque analysis and actuator selection

The forces and torques involved during the transition between planes depend on their orientation relative to gravity acceleration vector. This means that the loads which the mechanism will have to support will be different when the transition is made between the ceiling and the vertical wall or between the ground and the vertical wall, as shown in Figure 29.

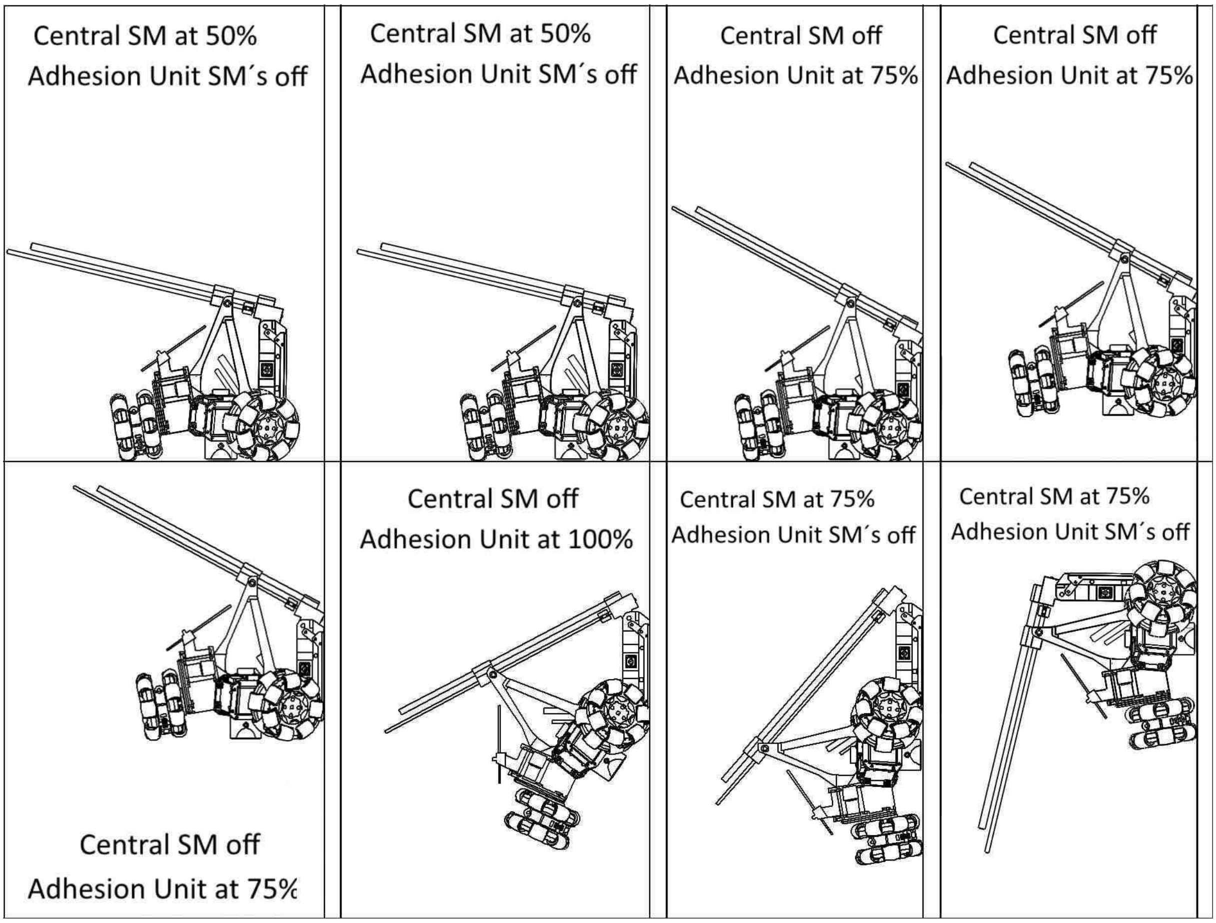


Figure 28: Plane transition process with the new mechanism.

These cases were studied and the actuators used in the transition mechanism were dimensioned taking into account the requirements for the most demanding transition.

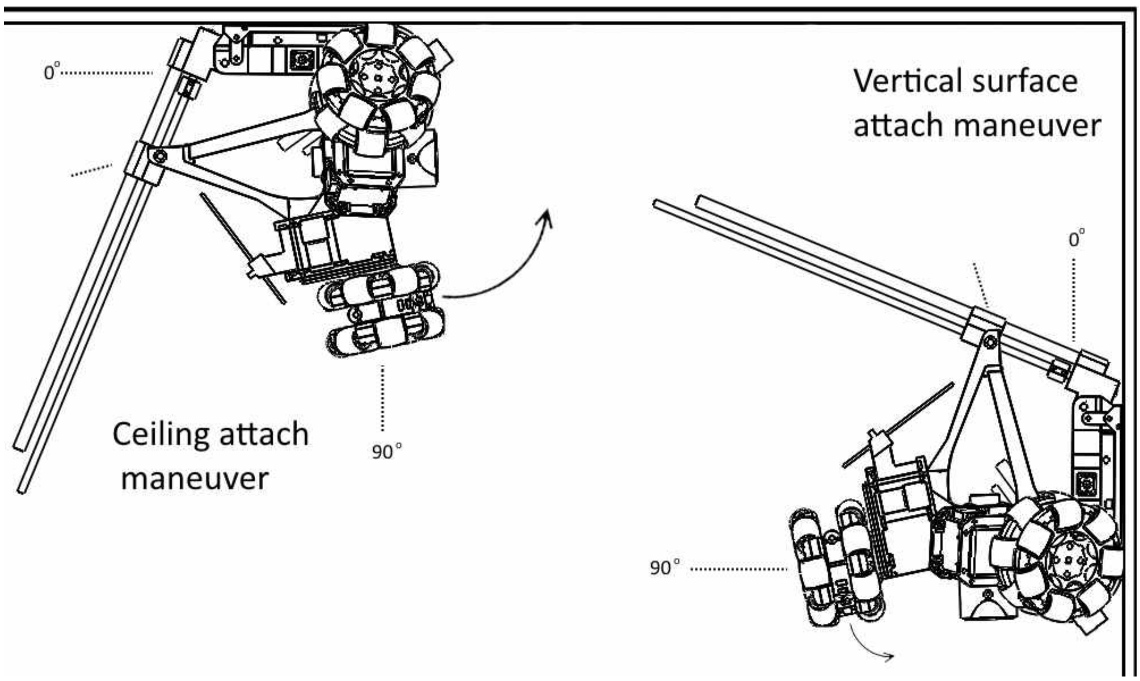


Figure 29: Ceilling and Vertical Wall Maneuvers

The mechanism should provide the required torque to rotate the joint in the worst case scenario, which is the passage from a vertical wall to the ceiling. As can be seen in Figure 30, we have:

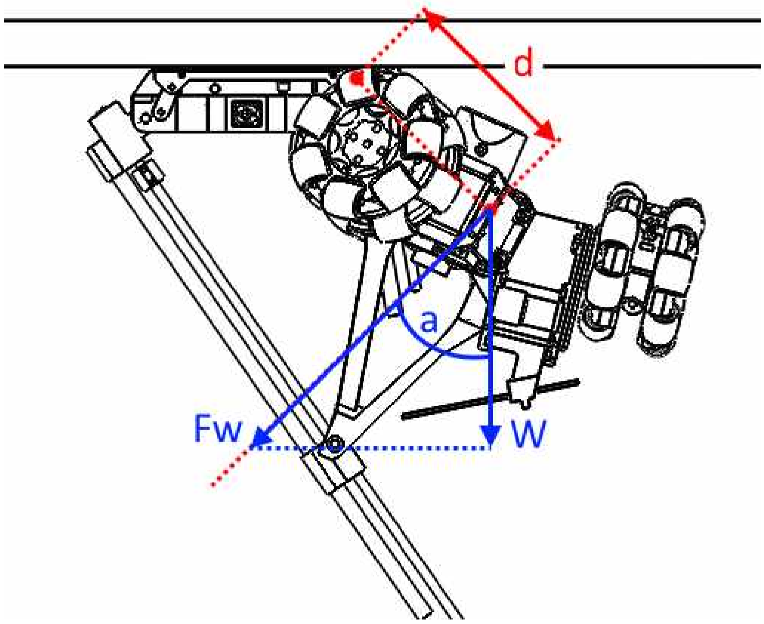


Figure 30: Gravity force and weight vectors during the ceiling attach maneuver.

Weight [N]; $F_w = W \times \cos(\alpha)$

Torque [Nm]; $T = d \times (W \times \cos(\alpha))$

Here α is variable during the transition and d. represents de distance between the center of the mass of the robot and the joint C on the arm adhesion unit.

Based on these results the actuators for the linear guides are selected. Due to the large contact area between the threads of the nut and the threads of the shaft, there is a huge loss of energy in friction so we considered just a 20% efficiency for the screw-nut system. The force generated by threaded shafts can be calculated as:

$$F_{out} = \left(\frac{2\pi \times T_{in}}{p} \times \eta \right) \tag{11}$$

Where F_{out} determines the generated linear force and T_{in} is the torque of the chosen motor. F_{out} is also the force that the shafts applied in the joints A and D. This force must be sufficient to counteract the weight of the robot and force this to return its position after the transition. In the worst scenario the force F_{out} applied in joint A must generate at least 1.32 Nm, as depicted in Figure 35. p is the pitch which is 0.5mm for an M3 screw, and η is the efficiency. The selected actuators are Pololu Micros Hp with a gear ratio of 100:1 and a nominal torque of 0.21 Nm at output shaft. This corresponds to a force of 0.53 N, assuming an efficiency of 20%.

This actuator is quite small. It has a cross section of 10×12 mm with a length of 26mm and weights approximately 10g. The high transmission ratio not only allows the use of smaller actuators, it also makes the system not non back drivable, having as a consequence the increase in transition time. Nevertheless, this does not seem to be critical since the plane transition is not a very frequent action.

4.3 Mechatronics

The new version of the Omniclimber integrates seven actuators from two different series (compared to four actuators in the previous version of the hand from a single servo, i.e. dynamixel actuators). Therefore, the control of the robot is more complex. In order to avoid integration of several drivers and control boards, we opted to design an ad-hoc single board control unit for processing, for driving all actuators of the robot and the arm, and also for communication. Figure 31 shows the schematic of the control unit and also the home-made board.

The integrated micro-controller is an ARM Cortex STM32F4. The Dynamixel servos of the climbing robot use a TTL protocol. To communicate with the micro-controller's the TTL must be converted from half-duplex to full-duplex. This is accomplished using a Buffer (SN74LS241DW) to switch between UART's TX and RX. The servos are connected in a Daisy Chain configuration which means that all servos receive all communication messages and select which message is for him by searching for a message with an ID that matches its own.
The Gear motors of the arm and the switchable magnets are driven with PWM using a H-Bridge (DRV8801PWP). They are equipped with magnetic Rotary encoders that communicate with micro-controller trough SPI.
The communication between the board and a ground computer is achieved through a Bluetooth module which is integrated into the board. The ground computer communicates with the micro-controller trough UART and is used to establish communication with a computer where the User interface is running. Furthermore the board integrates a connection point to a Raspberry PI. This means that a Raspberry PI single board computer can be directly plugged into the board. Currently we use the Raspberry PI only for communication of videos to the ground computer through wi-fi. In the next versions we will use this single board computer for achieving some part of the high level control on the robot rather than on the ground computer. The motors and Dynamixel servos are powered directly by a 3S Lipo Battery (12V) while the voltage is regulated to 5V to power the electronics.

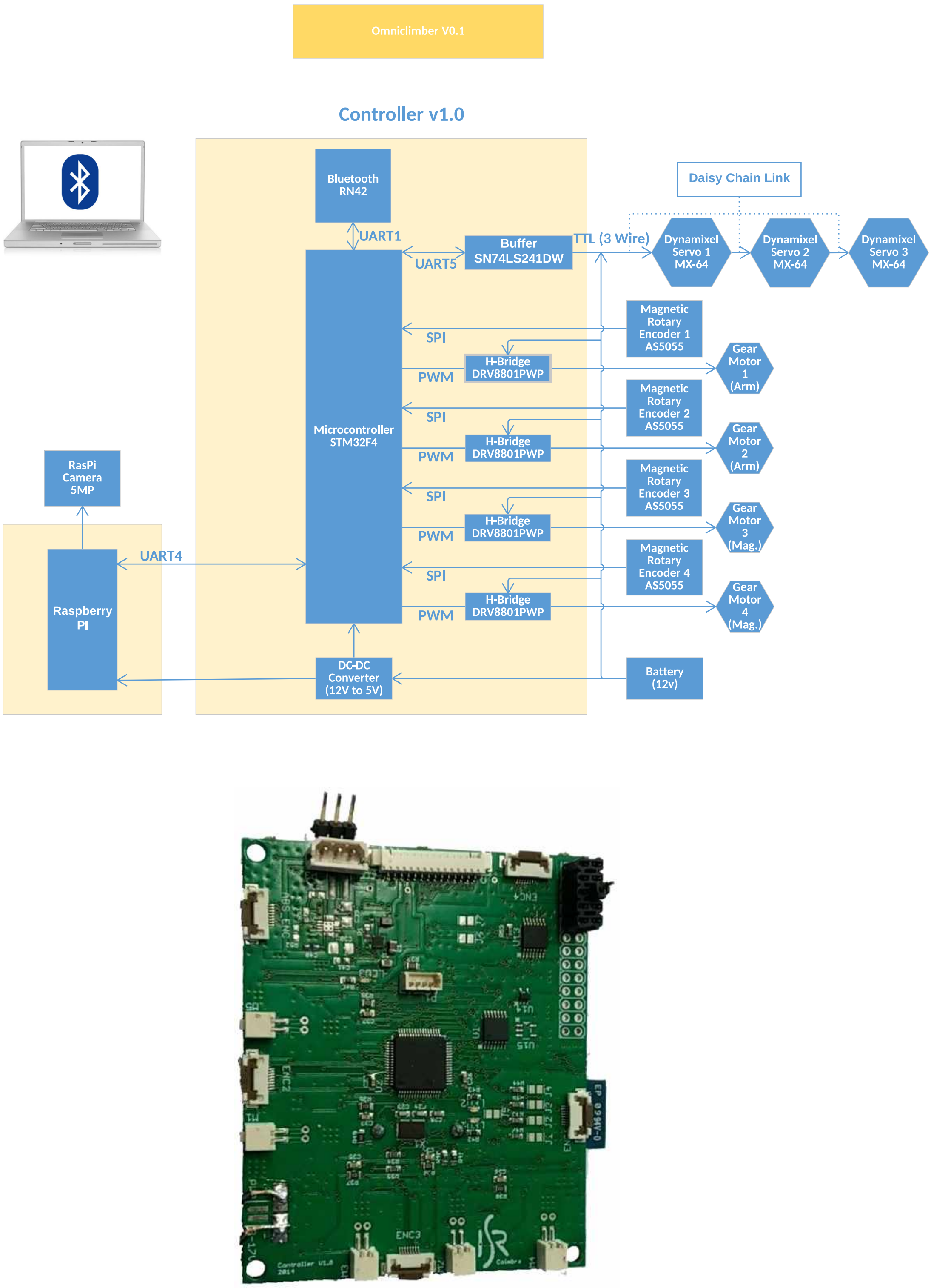


Figure 31: The schematics of the processing and control unit

5 TESTS AND RESULTS

Figure 32 shows the new prototype of the Omniclimber. The OmniClimber was tested on structures made of 1 mm thick steel sheets.

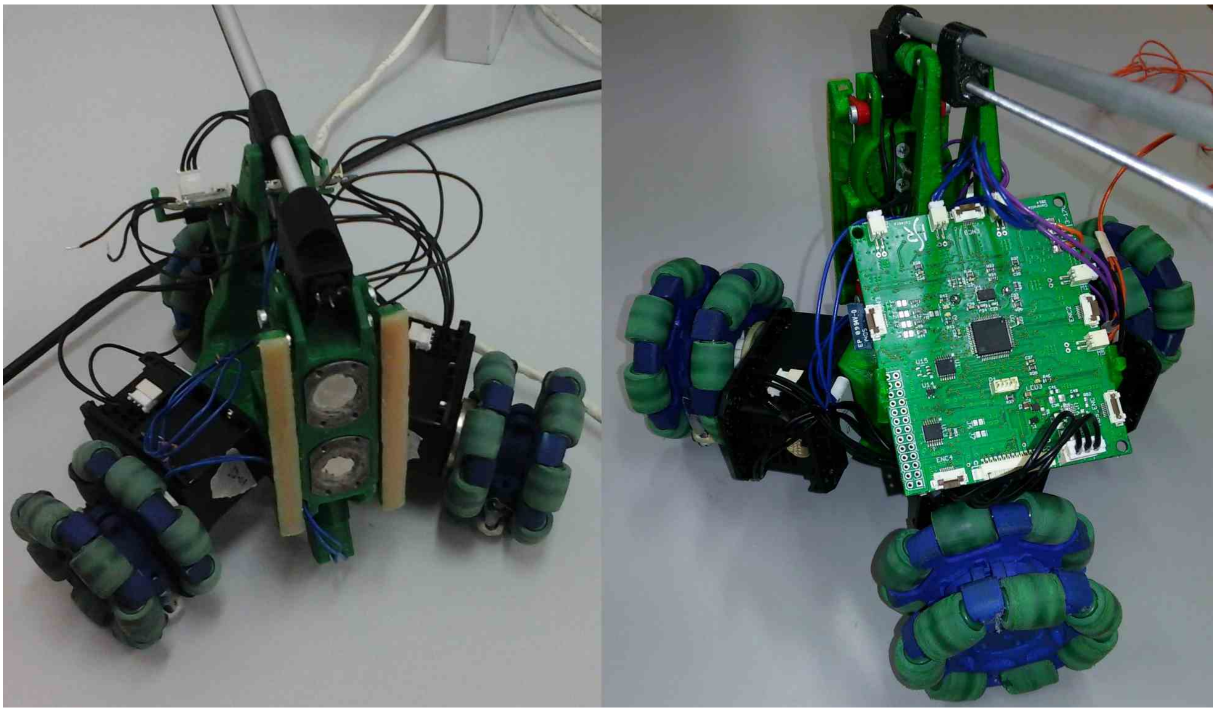


Figure 32: The new protoype of the Omniclimber

Figure 33 shows the passage from the floor to the wall, and Figure 34 shows the passage from the wall to the ceiling.

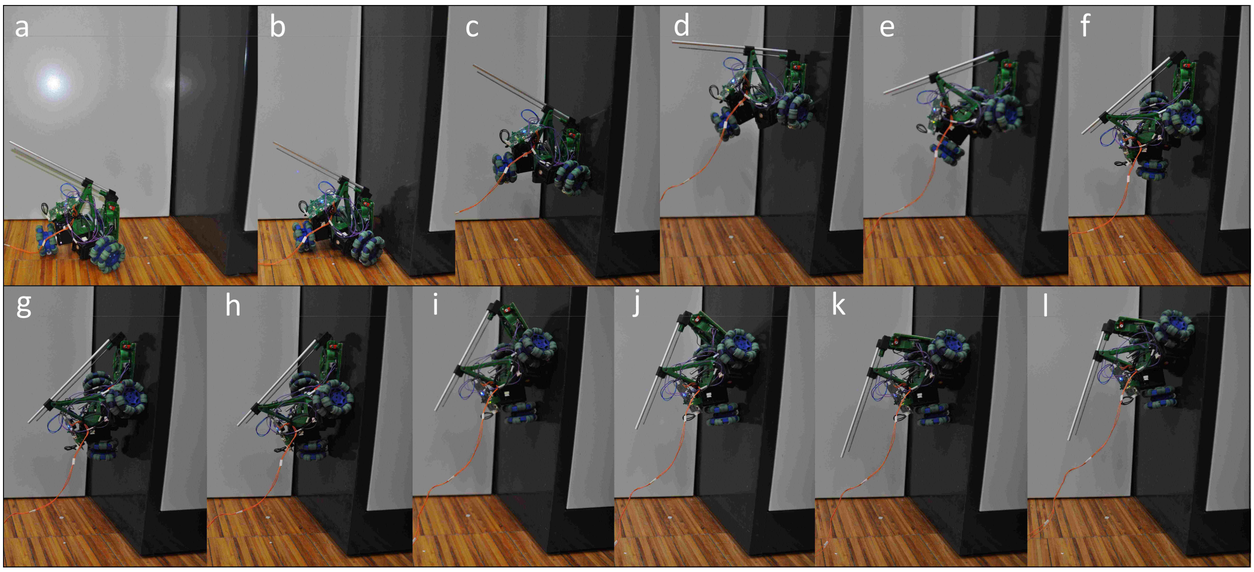


Figure 33: Video frames of the robot performing the transition between the floor and a vertical surface.

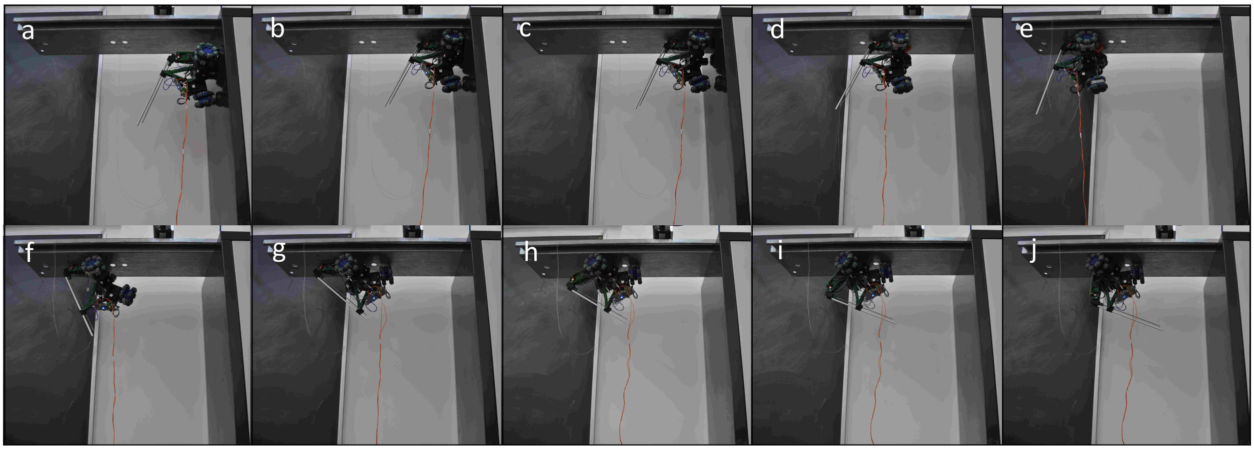


Figure 34: Video frames of the robot performing the transition between a vertical wall and a celling.

The graphs of Figures 35 and 36 show the state of the Switchable Magnets during transitions.

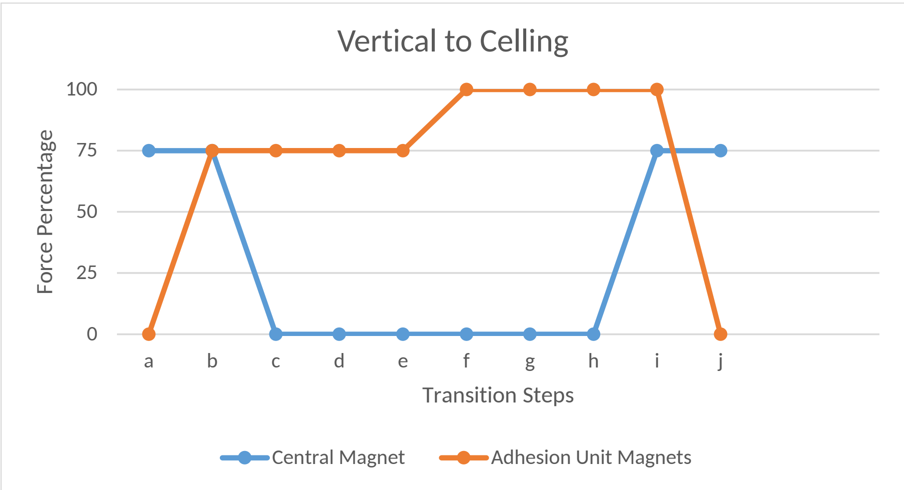


Figure 35: Wall to ceiling maneuver results

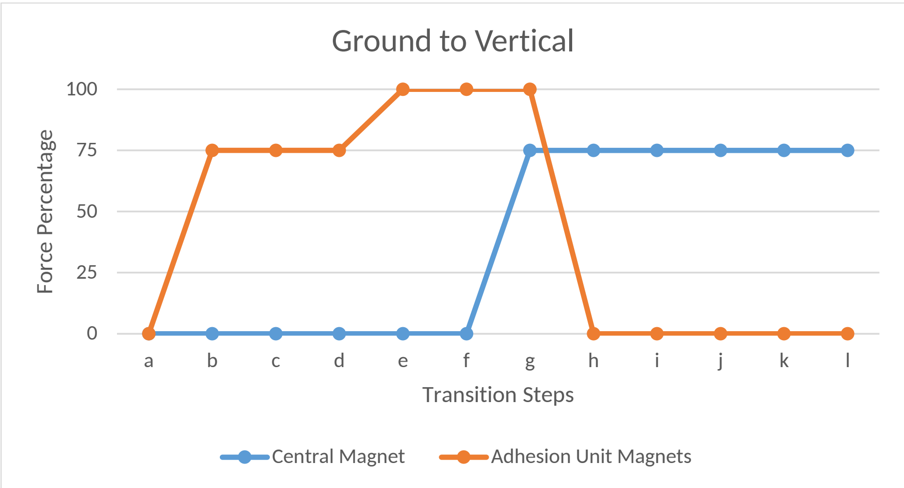


Figure 36: Floor to wall maneuver results

Compared to the previous version of the Omniclimber [1] which benefited from a minimalistic approach in terms of actuation (i.e. only four actuators for the whole robot), this version is more complex and integrates seven actuators. Furthermore the mechanism have a better control over the arm resulting in a smooth transition action. Furthermore, in addition to the adhesion force of the arm's adhesion unit, the adhesion force of the chassis to the structure can be controlled with switchable magnets. The non back drivable actuation system for the SM units result in a lower power consumption compared to electromagnets since the power is consumed only in the act of switching. This is also safer than electromagnets in case of a power failure. One drawback of the novel Omniclimber is its relatively slow transition which takes 15 seconds for a 90^o plane transition.

The characteristics of the OmniClimber version VII are presented in Table 7:

Table 7: OmniClimber VII characteristics

Diameter x height Total Mass	260 x 140 mm 1120 g
Total number of actuators	7
Total number of DOFs	5
Mobile robot Actuation	3 Dynamixel MX-64 rotary actuators
Arm Actuation	2 Pololu gear motors
Switchable magnets actuation	2 Pololu gear motors
Mechatronics and control	ad-hoc home made control unit with ARM cortex microcontroller
Power	Onboard LiPo 1000 mAh battery
Wheels	3 Omnidirectional Magnetic Wheels 70mm diam.
Adhesion force*	32 N (chassis switchable magnet *off*) 88 N (chassis switchable magnet *on*) 2x56N (arm adhesion unit)
Max climbing speed	14 cm/s
90^o plane transition time	15 s
Max payload	1500 g
Movement	omnidirectional

Regarding the weight reduction from the old version to the new one the reduction was approximately 30%. This was achieved by reducing the number of metallic parts such as bolts and shafts, and optimizing the density of each printed piece according to its function. The weight of the former transitional system was one of its major flaws so the new system was designed to be much lighter, without losing its effectiveness.

6 CONCLUSIONS

In this work it was proposed a novel plane transition mechanism for the Omniclimbers based on switchable magnet units that can be controlled for precise adhesion force control. These mechanisms were simulated, designed and fabricated. The SM units were customized for the specific applications considering our aim to reduce the detachment torque and also maximize the force per mass ratio for thinner structures. SM units were installed on the arm and on the chassis of the robot. The SM on the chassis replaced the previous permanent magnet of the chassis. In this case it is possible to choose the adhesion force based on the climbing structure. The transition arm is composed of high ratio transmission mechanisms i.e. a 100:1 lead screw nut mechanism. The inverse kinematics of the transition mechanism was also presented. Furthermore we designed, developed and integrated a home-made compact control unit that integrates the drivers and performs the closed loop control for all actuators and communicates with a PC through Bluetooth. The adhesion unit can be positioned accurately on the structure and is capable of raising the entire robot smoothly. The use of the switchable magnets allows for control over adhesion force which is necessary during transition and climbing. The precise control of the force generated by the magnets proved to be important for navigation and to switch between planes. Furthermore, adjustment of the adhesion force during the climbing is made easier. The use of linear guides with threaded shafts is an effective way to achieve accurate movements with high force,small actuators and also to have a non-back drivable system. In this way the arm can stay at any position without power consumption. However, this becomes at the cost of a slow transition. Yet this is not critical since the transition does not happen very often. The novel SM based adhesion unit and also the novel transition arm showed several advantageous over the previous version. This new design allows better control of the transitions of the robot, by controlling its movement with two actuators instead of one, without increasing the robot's weight. The new version is 30% lighter and enables a smooth motion. The reduced power consumption obtained by the use of switchable magnets, when comparing to electromagnets, potentially increases the autonomy and range of the OmniClimber. Another advantage of using switchable magnets is that it makes the robot safer in the event of power failure, and enables adhesion force control, giving better adaptability to different surfaces. Experiments showed that the mechanism works as predicted and it is a viable solution for wheeled climbing robots. Current transition time is 15 seconds. Future works will mainly focus on integration of proximity sensors on the arm and on the chassis and algorithms to make the transition autonomous. The main limitation which will be subject of the future work is the ability to adjust the required force for the SM unit of the chassis based on the material and surface condition. In this way we can autonomously control this force. This will be achieved by measuring the wheels slippage by comparing the velocity of the wheels (measured by encoders) and the distance that the robot traveled (measured by an optical sensor).

6.1 Publication

The article entitled ”The hybrid OmniClimber: Wheel based climbing, arm based plane transition, and switchable magnet adhesion” has been submitted to the 2015 Journal of Mechatronics, and is currently awaiting acceptance

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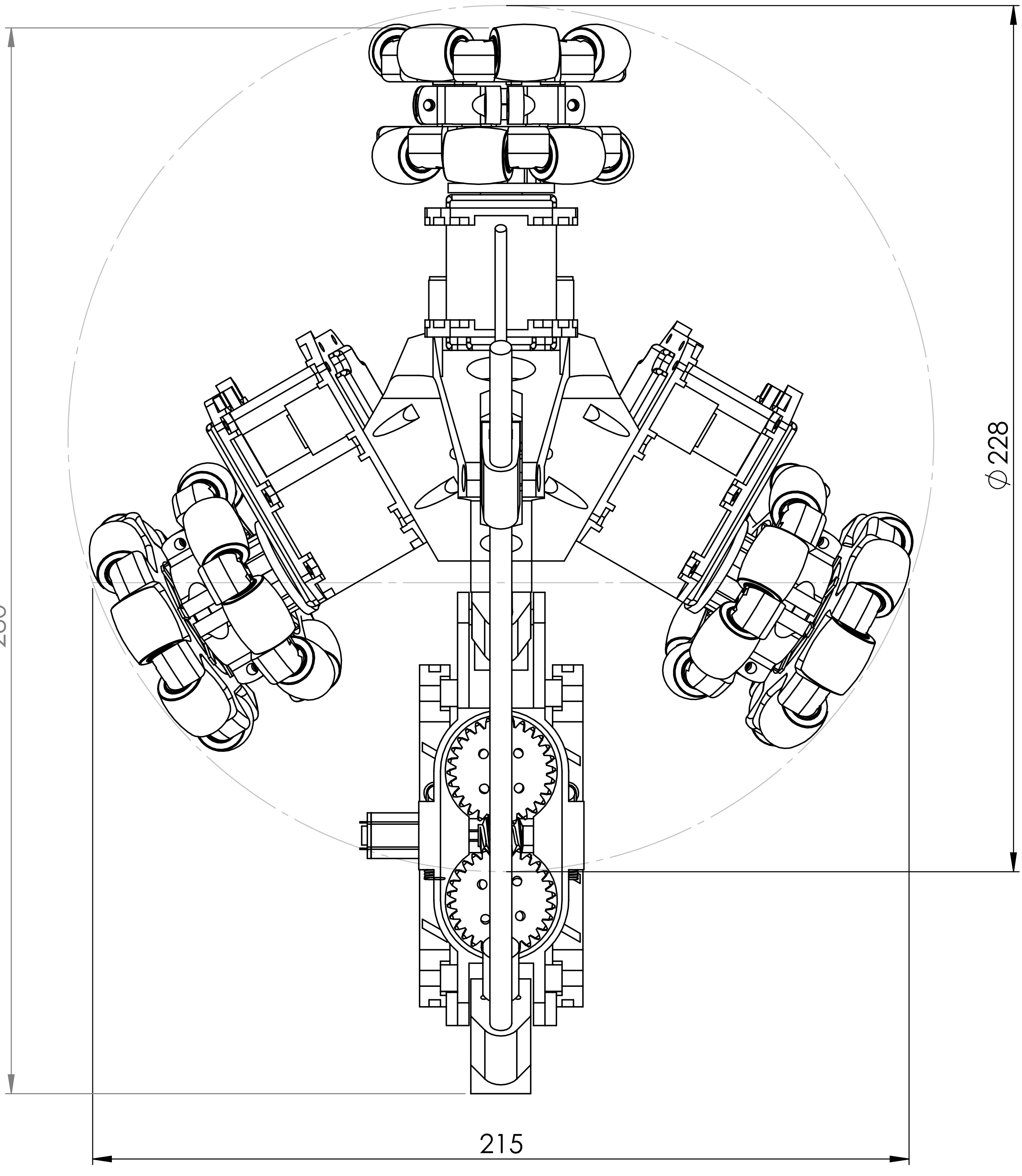
Appendices



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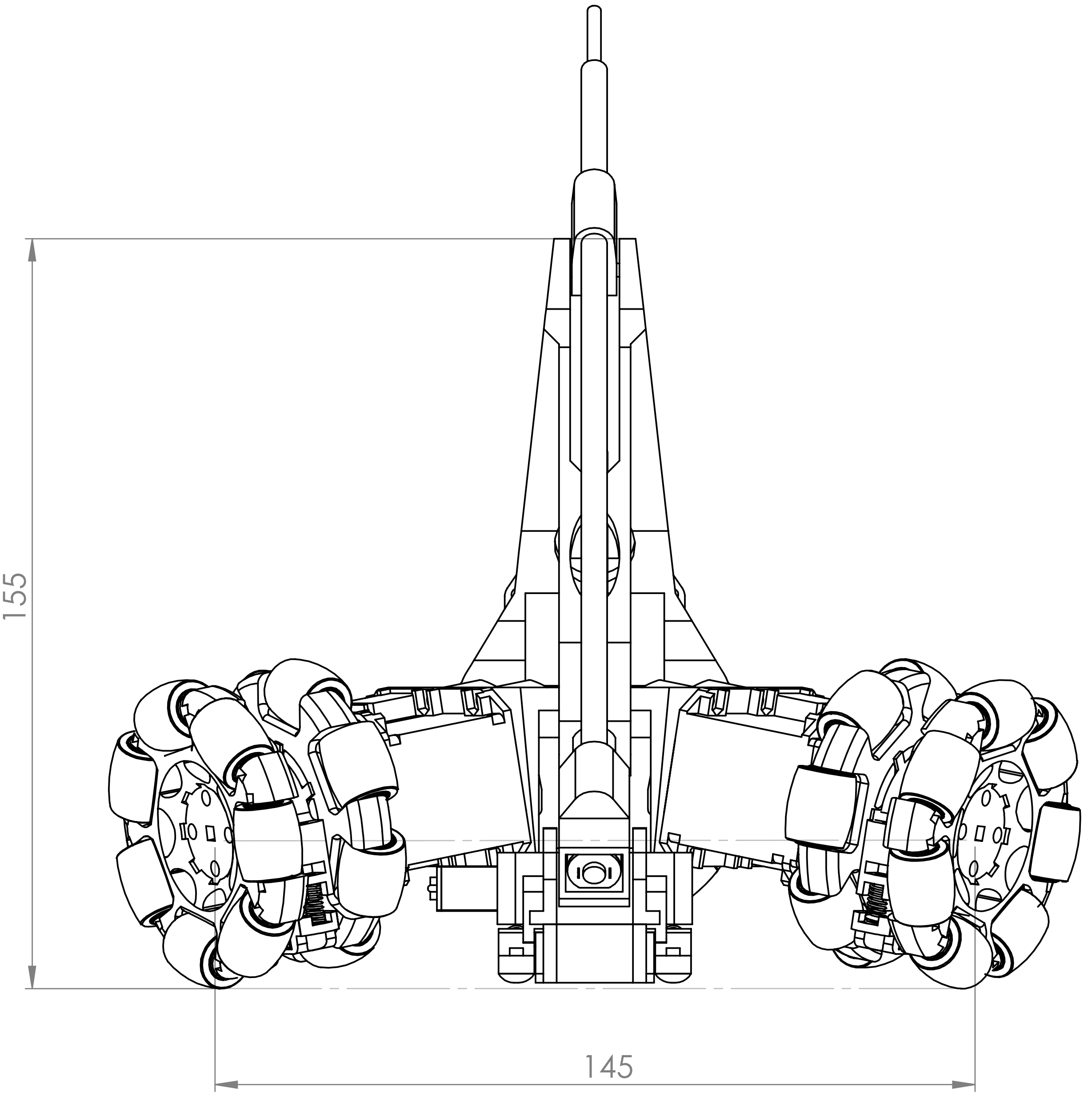

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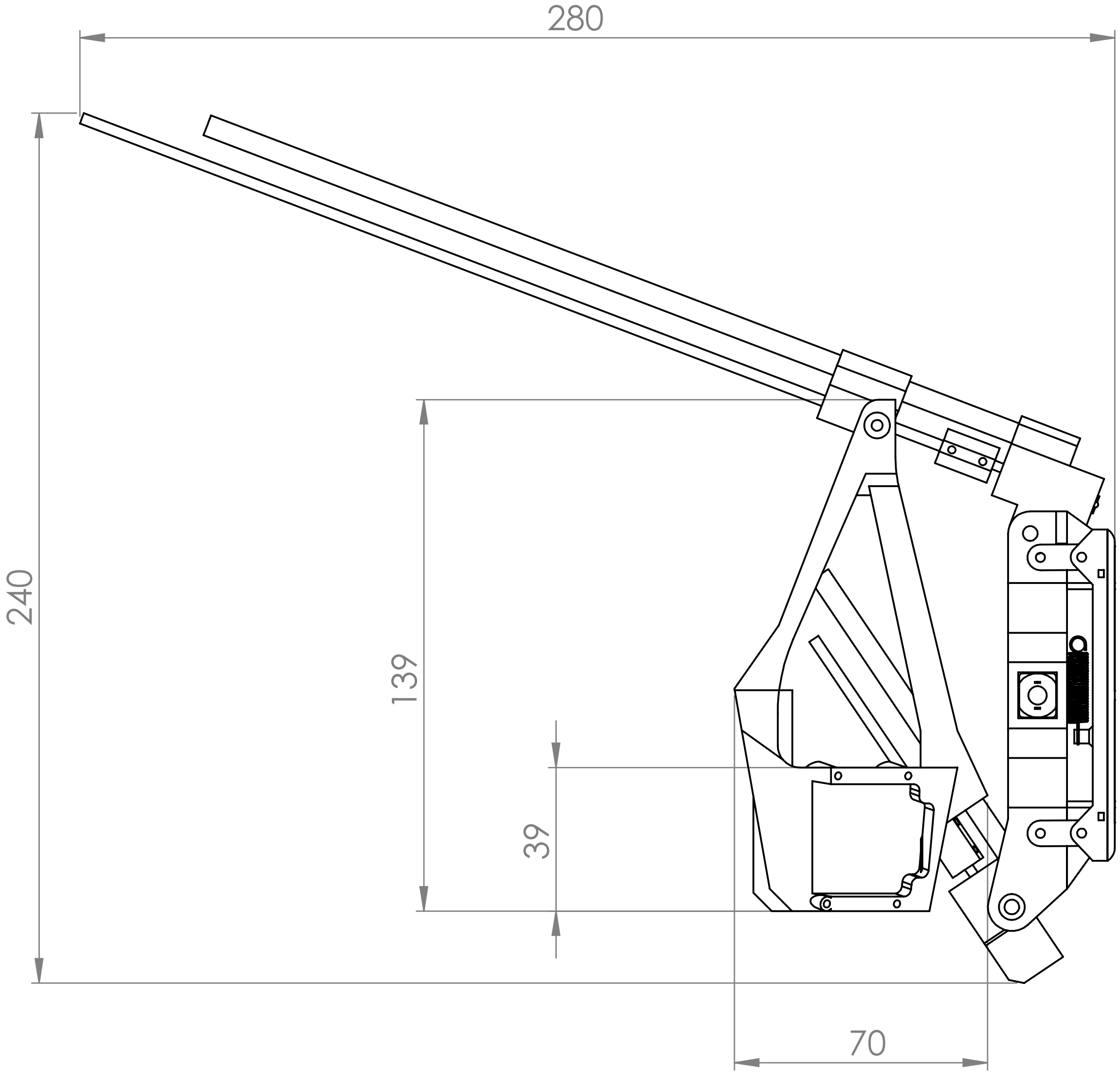

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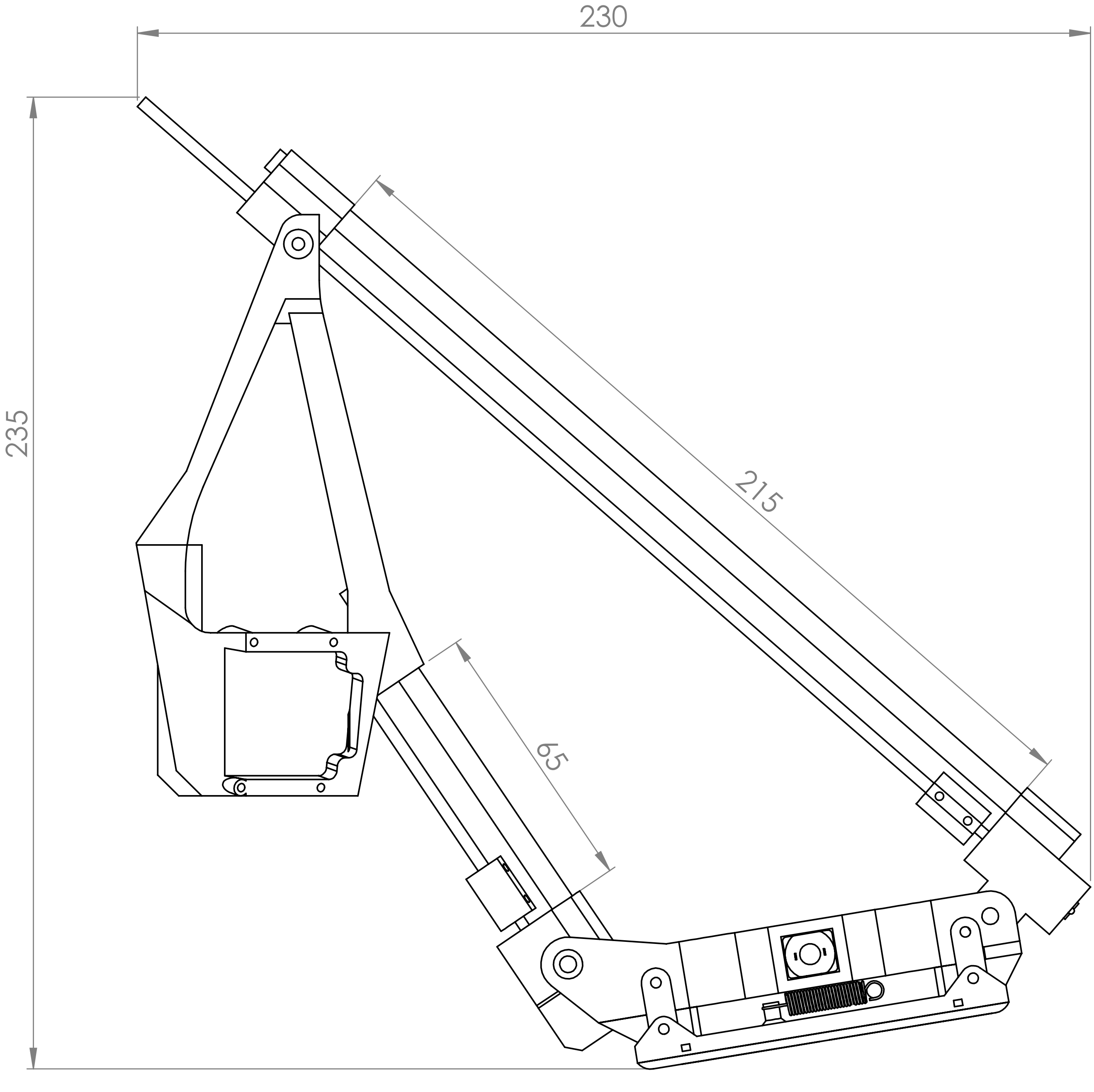

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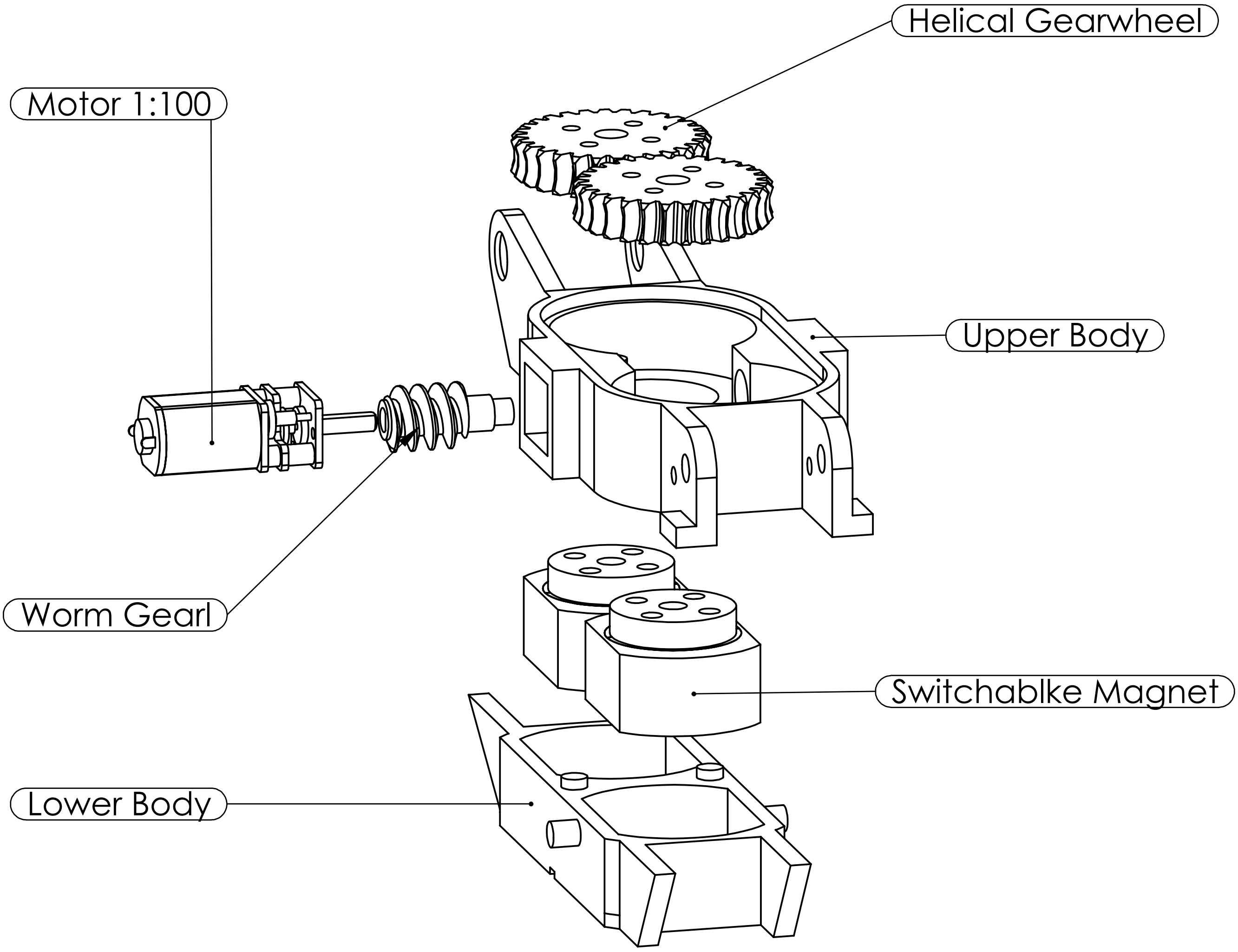

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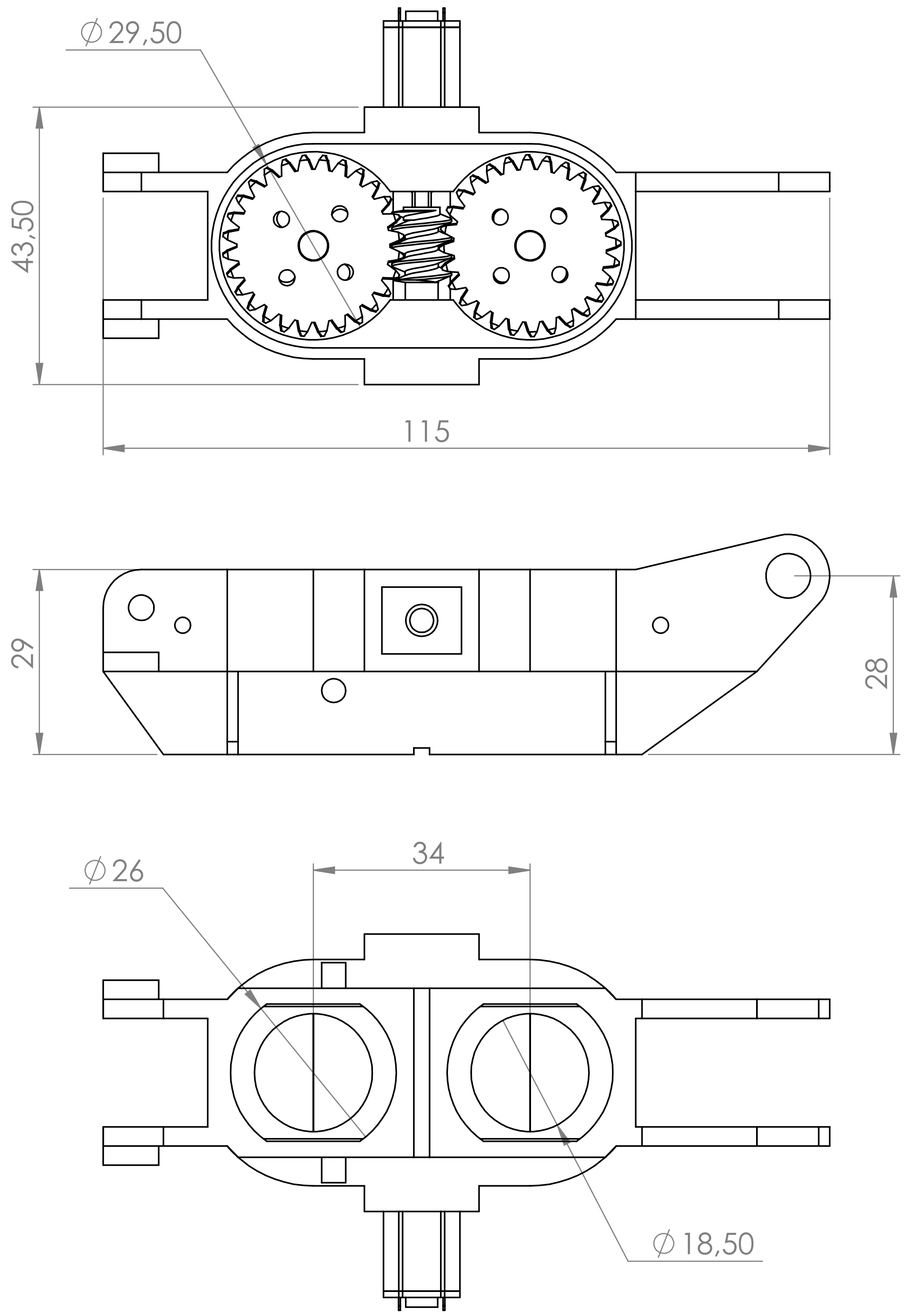

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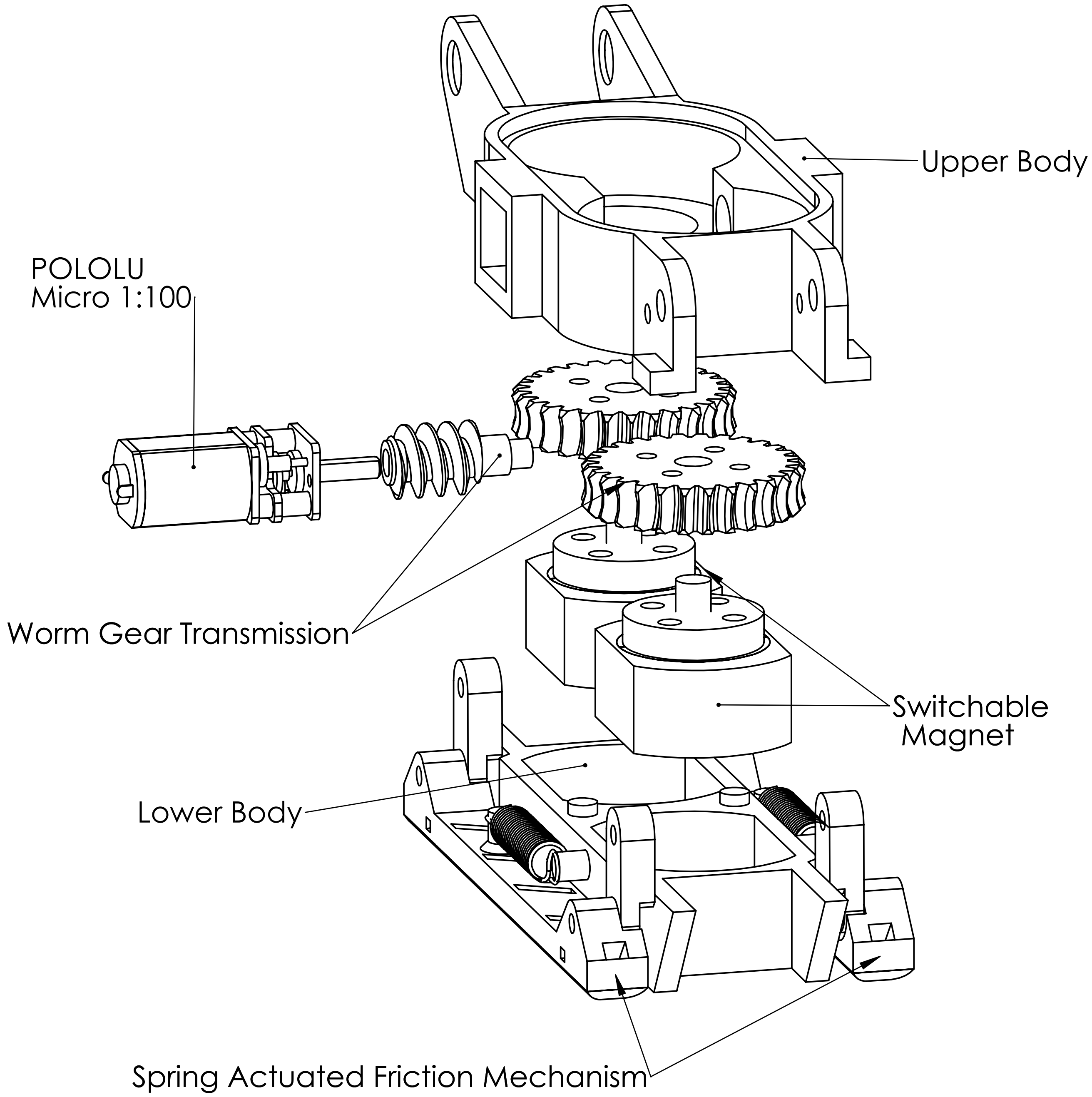

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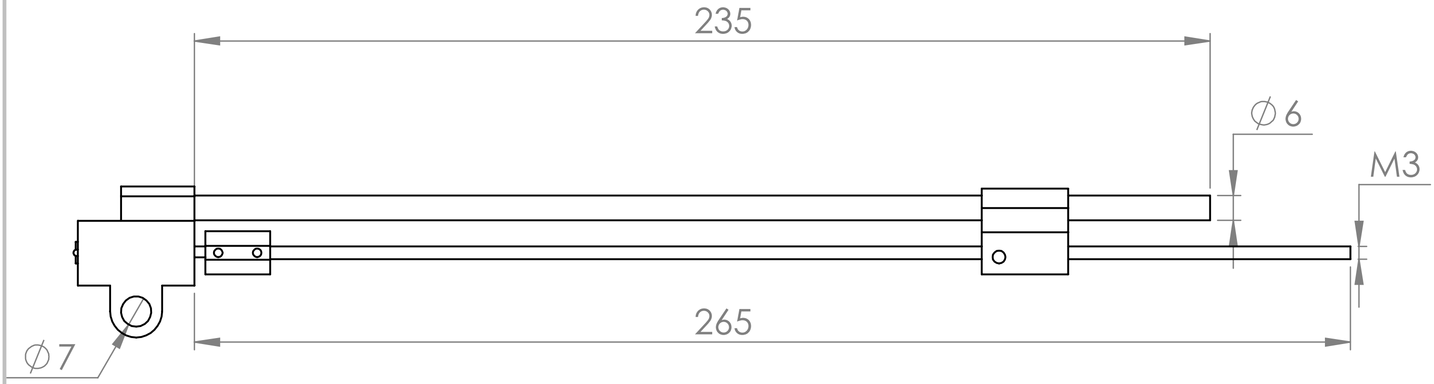

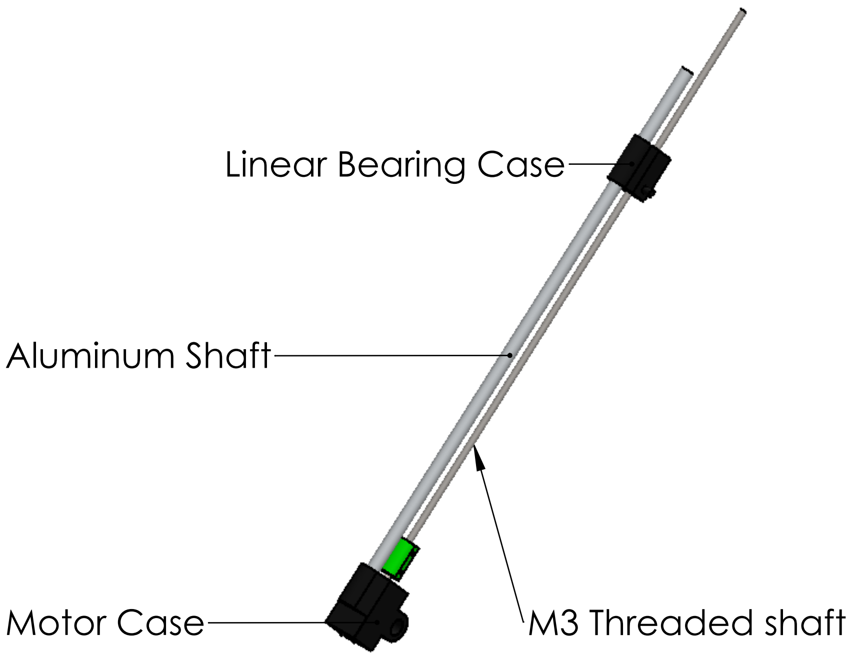

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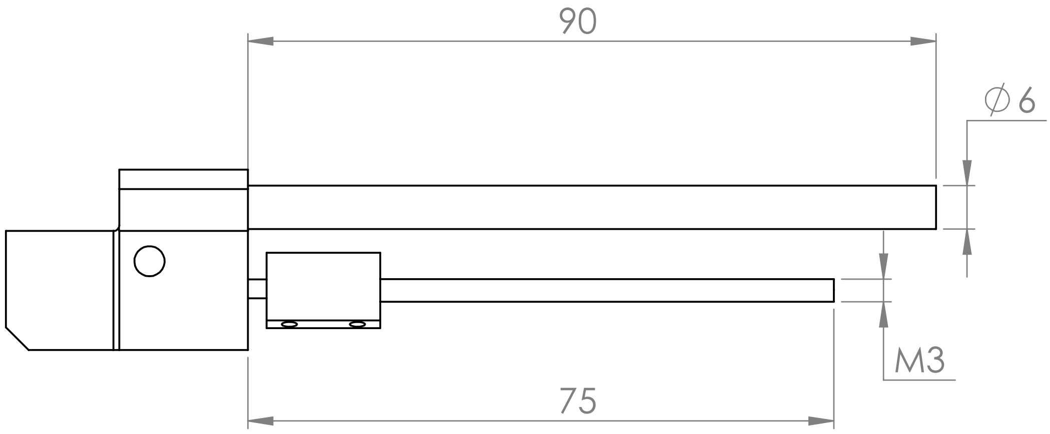

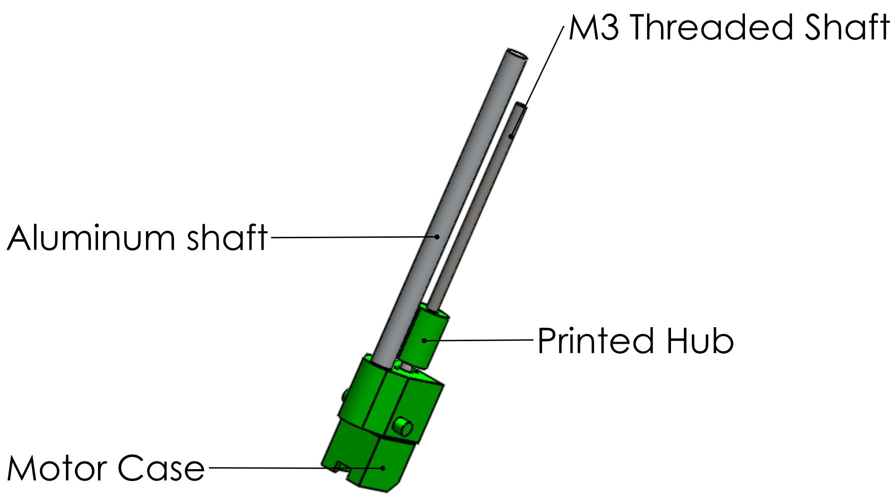

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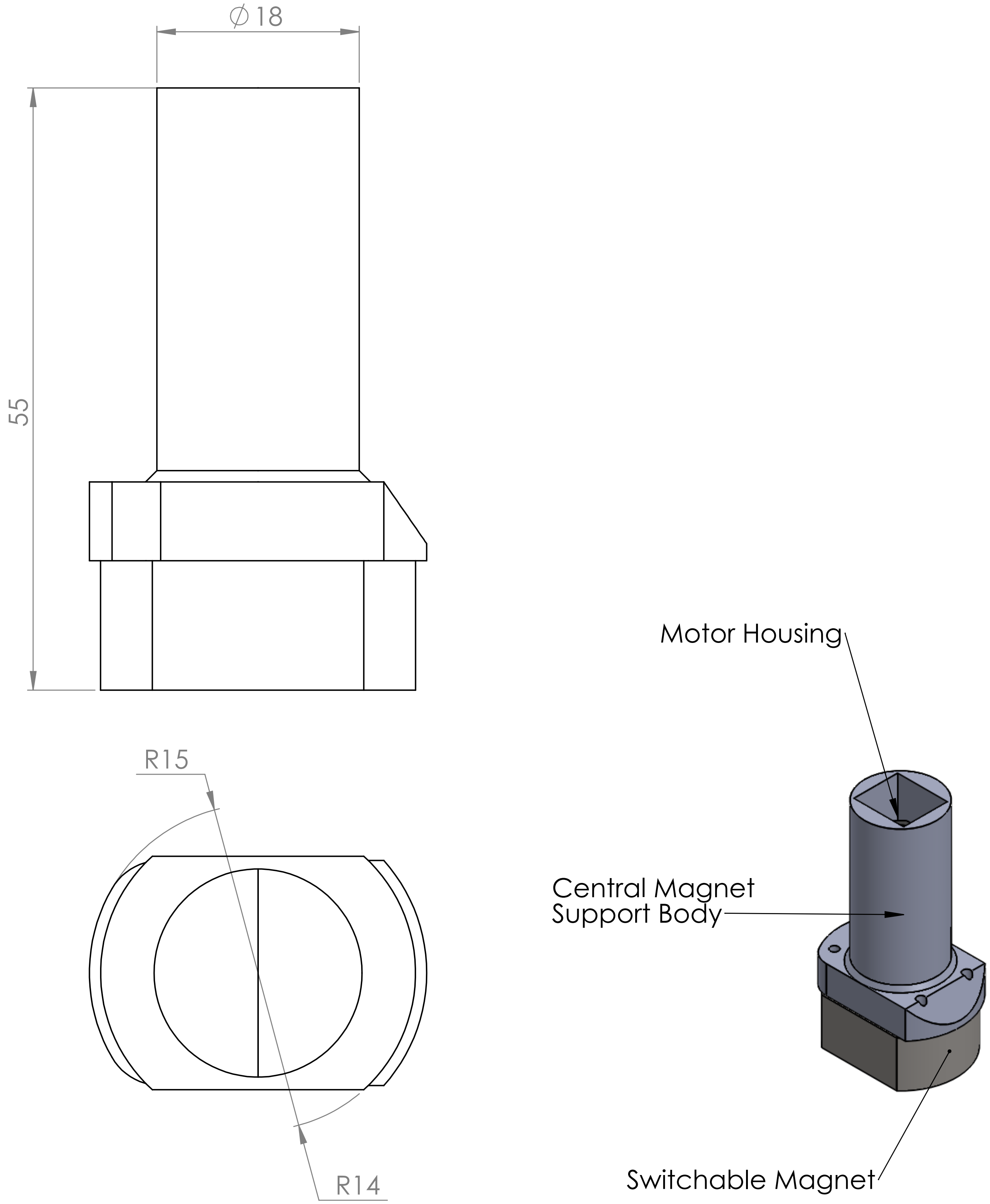
Q.A				MATERIAL: Several	DWG NO. 9	A4
				WEIGHT:	SCALE:1:2	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH:---------------------- TOLERANCES: 0.25 LINEAR: ANGULAR:		FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	João Lourenço		2015/09		OmniClimber	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: PLA	DWG NO. 10	A4
				WEIGHT:	SCALE:2:1	SHEET 1 OF 1