Tampereen yliopisto

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DESIGN AND CONTROL OF A WALL DRIVING ROCKER-BOGIE ROBOT

Faculty of Engineering Sciences
Master of Science Thesis
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ABSTRACT

OLLI RANTANEN: Design and Control of a Wall-climbing Rocker-bogie Robot
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Wall-climbing robots have been developed for decades for different inspection, surface finish and research purposes. However, there are still limitations in traversing on, and between, different surfaces. Many robots are either limited on smooth surfaces or may not be able to cross obstacles due to low ground clearance. Rocker-bogie suspension has proven its capabilities on multiple planetary rovers developed by NASA. The system is simple and provides a large trajectory and good steering capabilities. Therefore, it would be interesting to research whether the suspension capabilities could be implemented in a wall-climbing robot.

The aim of the thesis was to identify design features affecting the design process of a wall-climbing robot with ability to move on different surfaces and cross obstacles. In addition to this, three different adhesion method concepts were developed, which were compared using the criteria identified. The method seen as the most suitable was used to develop a prototype robot and the performance of the robot was tested with empirical experiences.

The most important factors for robot performance are seen the ability to attach to the surface it is moving on, and the ability to climb and avoid different obstacles. Rocker-bogie suspension ensures the ability to move and cross obstacles, but on vertical surfaces an adhesion method is required to work together with the suspension. The robot prototype is combining the chosen adhesion method to rocker-bogie suspension. The locomotion and adhesion capabilities on inclined surfaces were tested. The adhesion was found to be insufficient for vertical surfaces due to lack of power, but the prototype robot is capable of moving on inclined surfaces it wouldn't be able to without any additional adhesion.

TIIVISTELMÄ

OLLI RANTANEN: Seinällä kiipeävän rocker-bogie robotin suunnitteleminen ja ohjaaminen
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Avainsanat: rocker-bogie jousitus, seinällä kiipeävä robotti, kehitys, pneumaattinen kiinnitys

Seinillä kiipeäviä robotteja on kehitetty vuosikymmeniä erilaisiin tarkastus, pintakäsittely tai tutkimustarkoituksiin. Robottien kyvyssä liikkua erilaisilla pinnoilla, tai niiden välillä on kuitenkin puutteita. Monien robottien liikkuminen on rajoittunut joko sileille pinnoille, tai ne eivät kykene ylittämään esteitä vähäisen maavaran vuoksi. Rocker-bogie jousitus on osoittanut kykynsä liikkua vaihtelevassa maastossa NASAn mönkijöissä. Järjestelmä on yksinkertainen ja takaa laajan liikeradan sekä hyvän ohjattavuuden, minkä vuoksi onkin mielenkiintoista tutkia, voitaisiinko sen kykyjä hyödyntää seinällä kiipeävässä robotissa.

Tässä diplomityössä on pyritty tunnistamaan asioita, jotka vaikuttavat vaihtelevassa maastossa toimivan seinällä kiipeävän robotin suunnitteluun. Tämän lisäksi kehitettiin kolme eri kiinnitysmetodin konseptia, joita vertailtiin laitteelle asetettujen vaatimusten näkökulmasta. Näistä parhaimpana pidetystä metodista kehitettiin robotin prototyyppi, jonka toimintaa voitiin tarkastella empiirisillä kokeilla.

Tärkeimpinä tekijöinä robotin toimivuudelle on riittävä kyky kiinnittyä kuljettavaan pintaan, sekä mahdollisuus niin väistää kuin myös ylittää esteitä. Rocker-bogie jousitus takaa kyvyn liikkua ja ylittää esteitä, mutta toimiakseen pystysuorilla pinnoilla vaaditaan lisäksi kiinnitysmetodi, joka toimii yhdessä jousituksen kanssa. Robotin prototyyppi yhdistää kiinnittymismetodin rocker-bogie jousitukseen. Tätä prototyyppiä testattiin niin liikkumiskyvyn, kuin myös kallistettuun tasoon kiinnittymisen osalta. Prototyyppi ei kyennyt liikkumaan pystysuorilla tasoilla kiinnitysmetodin puutteellisen tehon vuoksi, mutta se kykeni liikkumaan jyrkempään kulmaan kallistetuilla tasoilla, kuin mihin robotti ei olisi kyennyt ilman kiinnitysmetodia.

PREFACE

This thesis is done for VTT with the intention to research possibilities of developing a wall-climbing robot with ability to move on varying surfaces and crossing obstacles. The thesis addresses the requirements concerning the design of such robot and some of the development work done in order to implement a prototype robot.

I would like to thank Ali Muhammad, thesis supervisor at VTT, for providing the subject and guidance during the whole process. Also, thanks to the thesis examiners Reza Ghabcheloo and Tero Juuti for their instructions, and input regarding the thesis writing. I'd also like to thank my coworkers Joni Minkkinen, Petri Tikka, Janne Lyytinen, and all the others who may not be mentioned here, but have provided feedback, help and ideas regarding different topics completely new and unknown for me.

Tampere, 9.3.2019

Olli Rantanen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

CAD	Computer Aided Design
EDF	Electronic Ducted Fan
LED	Light Emitting Diode
LiPo	Lithium Polymer battery
PPM	Pulse Position Modulation
PWM	Pulse Width Modulation
PC	Personal Computer
RC	Radio Control
RGB	Red, Green, Blue
RPM	Revolutions Per Minute
SBUS	Serial BUS
SI system	Système international d’unités, International System of Units

α	angle α
a	acceleration
A	area
β	angle β
F	force
F_b	buoyancy force
F_{duct}	force induced by duct
F_f	friction force
$F_{f\,acc}$	friction force required for acceleration
F_n	normal force
F_t	thrust force
F_{tot}	Total force
g	gravitational coefficient
G	gravitation force
G_x	x component of gravitation force
G_y	y component of gravitation force
h	height
i	ordinal
μ	friction coefficient
m	mass
m_{gas}	mass of gas
$\dot{m}$	mass flow rate
p	pressure
ρ	density
r	radius
r_{in}	inner radius of duct
r_{out}	outer radius of duct
s	distance
s_{pitch}	propeller pitch
t	time
v	speed
v_e	air velocity behind propeller
v_0	air velocity in front of propeller
V	volume
ω	angular velocity

1. INTRODUCTION

Wall-climbing robots have been researched for decades [24]. The main purpose of these robots is to climb on vertical surfaces, such as walls, completing different tasks [11]. Different solutions have been presented over the years and their complexity has varied from simple wheeled suction cups to spider-like legged robots, as seen in for example in Figure 1.

Figure 1. *Ibex [28] and MRWALLSPECT - III [16]*

The robots can handle tasks that might be dangerous or laborious for human workers. In case of wall-climbing robots this means operating in places that might be either dangerous due to the height or require considerable amounts of time or money to set up scaffolding in order to complete the task.

Wall climbing robots are mainly used for inspection, cleaning and maintenance purposes [11]. They can be used on buildings, on surfaces of large vessels such as ships, or containers like oil tanks. For instance, International Climbing Machines' (IMC) The Climber robot seen in Figure 2 is used to inspect wind turbines. Many wall-climbing robots are also done just in order to research certain adhesion methods, structural solutions or control systems.

Figure 2. IMC's The Climber robot inspecting wind turbine pole [17]

Moving on vertical surfaces requires good maneuverability, but especially good ability to efficiently attach to the surface robot is moving on. Multiple different solutions for both adhesion and locomotion has been developed [11][20]. In certain tasks, as moving versatilely between different surfaces in built environment or moving on natural surfaces, good traversing abilities and high ground clearance would be needed, yet they may not be the most distinctive feature of all wall-climbing robots.

1.1 Identification of the problem and objectives

Many wall-climbing robots have limited capability to either move on different surface materials or between different angled surfaces such as transition from floor to wall, as can be seen in review of the state of the art in chapter 2. Many of the robots reviewed seem to be either developed for rather precisely defined purpose in strictly defined environment or mainly for research purposes. The design solutions used affect their capabilities to work in different environments and to move between different surfaces and there seems to be few robots capable of doing both without limitations.

Rocker-bogie suspension, seen in Figure 3, is known to perform reasonably on difficult terrain and it is therefore used by NASA in their planetary rovers such as Sojourner, Spirit, Opportunity and Curiosity. The suspension should distribute the weight of the vehicle on all wheels, while also ensuring reasonable capabilities to cross different obstacles and keeping all of the wheels in contact with the surface. Therefore, it would be interesting option for locomotion system of a wall-climbing robot that should have good traversing abilities on different surfaces.

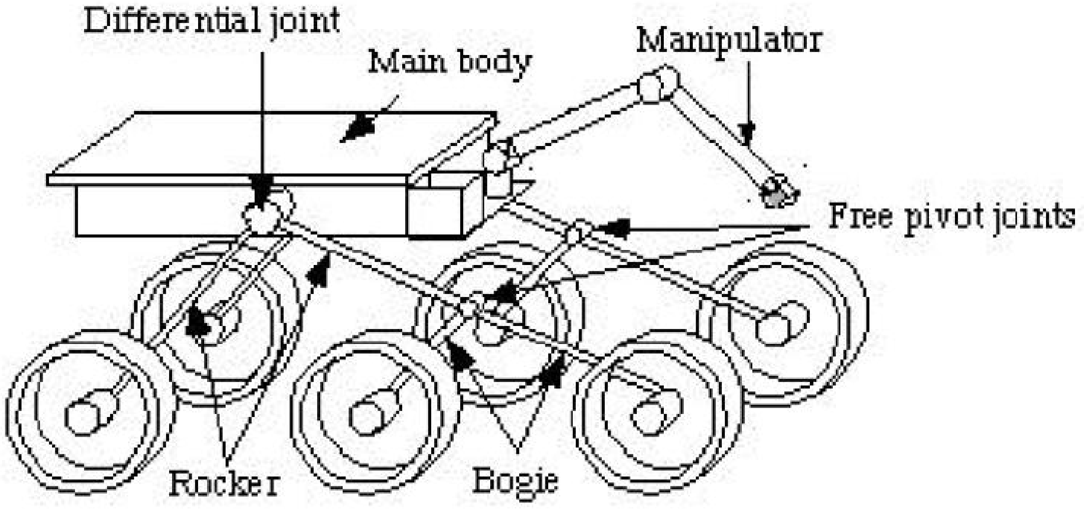

Figure 3. *Rocker-bogie suspension in a rover [8]*

In order to focus the research questions and objectives, the objective will be to research whether it would be possible to develop a wall-climbing robot utilizing rocker-bogie suspension and inspect the capabilities of such robot. Thus, the research work done will focus mainly on the adhesion method to be used.

However as similar robots haven't been implemented or documented before according the preliminary literacy research done for the thesis, it is not exactly clear what should be expected and required from such robot. Overall few different requirements are to be expected from wall-climbing vehicles and for example Guan et al. [15] list features desired from wall-climbing robot as following:

1. Attaching reliably on wall
2. Overcoming obstacles or gaps
3. Moving omnidirectionally
4. Transitioning between walls
5. Possible manipulator

These are general qualities to be required from if not all at least from most wall-climbing robots. However different purposes may have additional requirements and therefore one of the research problems is, what kind of design requirements should be expected from a wall-climbing robot with good traversing abilities.

This thesis aims to define more detailed requirements for a wheeled wall-climbing robot with good ground traversing abilities in chapter 4, which should be taken in account during the design process. Some of these criteria may resemble the ones defined by Guan et al., yet due to the nature of the thesis some may also be influenced by the possibilities and limitations targeted to the thesis work. Inspiration shall be taken from existing robots and their possible desired features or defects.

As the requirements are defined, one of the objectives is also to implement a prototype robot based on the criteria. This is done in order to inspect the capabilities of such device, but also to certify the design criteria and design process done. With actual implementation and empirical testing, possible defects and shortcomings can be detected and addressed, in order to continue the development work regarding wall-climbing robots with good traversing abilities.

In short, the objectives can be summarized as:

- Research the state of the art in order to identify possible good or bad features
- Define a criteria to compare and analyze different robot concepts
- Create possible concepts and compare them according the criteria
- Implement a prototype robot in order to test its capabilities as wall-climbing robot

1.2 Research questions, strategy and methods

As noted in previous chapter, one of the main research questions is what requirements affect the development of a wall-climbing robot in design phase, or what properties should be considered during the design. As the locomotion system principle was chosen to be the rocker-bogie suspension, the design will mainly focus on the adhesion method aimed to keep the robot on vertical surfaces.

Due to the motivation of the thesis being an attempt to research possibilities of developing wall-climbing robot with good traversing abilities, the design requirements shall be applied to a prototype robot that could be used to test the design based on criteria. Practical testing could find answer to the questions about possible capabilities of such wall-climbing robot with good traversing abilities, but also about how commercial products can answer the needs of such implementation.

Overall the research questions can be summarized to following:

- What kind of criteria affects the design process of a wall-climbing robot with good traversing abilities, and what kind of features should such robot have?
- What is the most suitable pneumatic adhesion method for a wall-climbing robot utilizing rocker-bogie suspension, if only one adhesion source is utilized?
- How does the adhesion method perform, when combined with rocker-bogie suspension?

Due to the diverse research questions a multistage approach was chosen. First the design criteria should be formed and based on properties seen in existing implementations of wall-climbing robots. Either demanding features seen as vital or avoiding possible defects observed in them. Thus, theoretical approach by reviewing the state of the art will be used here.

Based on this criteria small number of different concept designs can be created and further analyzed according the criteria. This is done in order to find a suitable concept for implementation and further testing, considering some of the limitations set for the thesis. Concepts shall be analyzed based on both theoretical calculations, but also on some assumptions made during the design process if there is not enough data available.

In second phase more empirical and experimental approach can be used. As one of the objectives is to implement a robot based on design criteria identified, the outcome of this design process should be tested. With empirical testing the capabilities of implemented robot can be studied, and practical implementation of the robot can be analyzed.

The testing shall be done by measuring the robots moving capabilities on inclined surfaces and observing the traversing abilities by crossing obstacles. Practical testing should also reveal more information about capabilities of commercial components used to build the robot, as theoretical concept design may not be able to take in account every detail and sometimes not enough information may be available. By testing a prototype also further design requirements may be identified to complement the ones identified based on the review of the state of the art.

1.3 Scope of the thesis

This thesis will address the mechatronic design of the robot, focusing mainly on the adhesion system. In addition to defining the design requirements, it will include an analysis of each concept and the forces keeping them on inclined surfaces. Based on the analysis, one concept shall be implemented and a description of the control system design for the adhesion method and overall robot control shall be given. Thus, the work done will be focusing on pneumatics and machine automation.

In addition to the adhesion system there will be also focus on the limitations and opportunities that the rocker-bogie suspension chosen for the vehicle may set. The suspension should offer higher ground clearance than conventional solutions seen before in wall-climbing robots, yet this might set certain limitations and requirements on the adhesion method, of which some may become obvious only during practical testing of the robot.

Even though implementing a prototype robot is part of the objective in this thesis, the thesis will not address all of the mechanical and electrical design required to implement the robot. Out of these viewpoints only the parts considered to be vital for the adhesion system will be accounted for. Potential defects or faults may be processed within the chapters focusing on testing the prototype. For example, the mechanical solutions implemented may affect the working of the robot or the control system designed for the robot. If such effects are discovered, these will be discussed on general level.

1.4 Structure of the thesis

This thesis is divided in 9 chapters. The chapters shall cover the state of the art, defining the main features required from a wall-climbing robot with good traversing abilities, development of adhesion system concepts for such wall-climbing robot, implementation of the robot and discussion and conclusions about the results achieved.

Chapter 1 of this document will focus on introducing the subject and the background, while also setting the research questions and the scope of the thesis. The second chapter is dedicated for discussion about the state of the art of wall-climbing robots and two of their most distinctive features; adhesion and locomotion.

The third chapter will discuss the theoretical background related to pneumatic wall adhesion methods and other mechanical features, such as the rocker-bogie suspension in detail. It will try to give an insight about the theoretical background required to understand different pneumatic adhesion methods and their possibilities.

In chapter 4 the design requirements for wall-climbing robot with good traversing abilities will be discussed. In fifth chapter three concepts for an adhesion method for such wall-climbing robot will be presented and their capabilities approximated based on theoretical calculations. These concepts will be compared against the criteria set in chapter 4 in chapter 6. One of these concepts will be chosen and the practical implementation of the robot will be discussed in chapter seven.

The testing and results of the practical work are collected and analyzed in the eight chapter. The methods used for implementation and testing will be also discussed and improvements suggested. The last chapter is a summary of the work done and will conclude the thesis.

2. STATE OF THE ART

Wall-climbing are mostly used to explore and inspect natural and built structures or to test, clean or maintain different vertical surfaces that either would not be accessible or would be too dangerous for a human operator. These robots can be anything from small inspection robot to a bigger and heavier robot being able to carry a payload or tools to do certain tasks.[11]

Wall-climbing robots have been developed since the 1960's [11][24]. The earliest examples were similar to the large sucker robot presented by Nishi and seen in Figure 4.

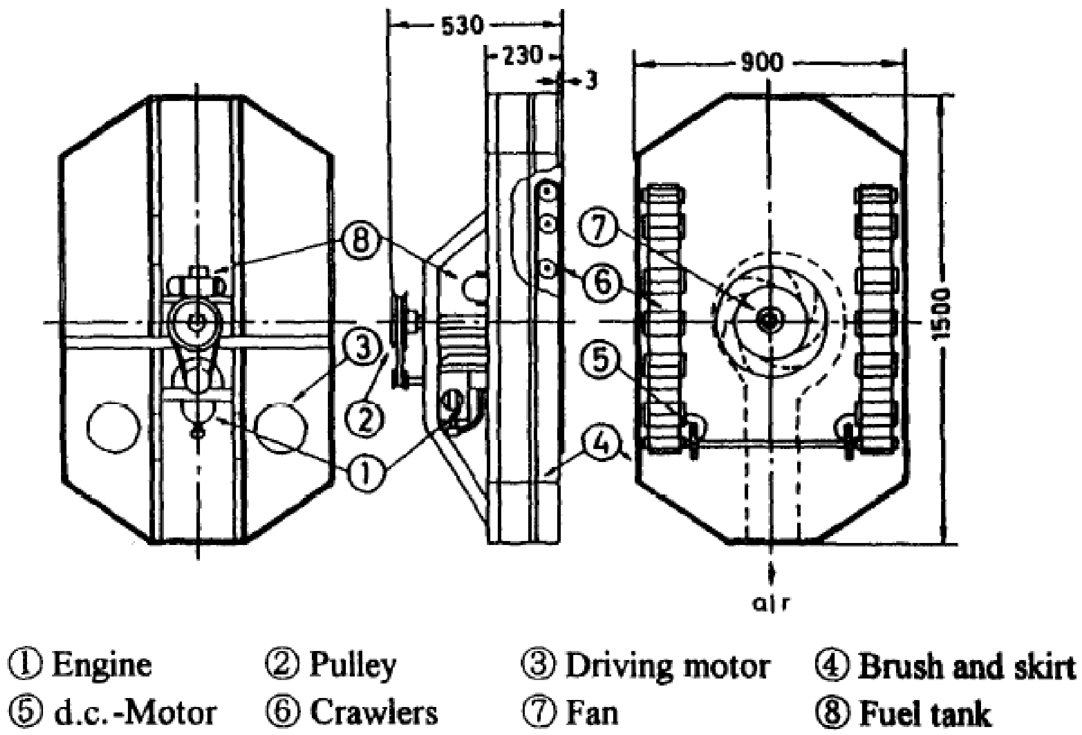

Figure 4. *A large sucker robot [24]*

The robot is based on single suction fan lowering the pressure below the robot. The locomotion is implemented with tracks and differential steering. As can be seen from the design, the robot is not capable of for example doing the transition from floor to wall. The clearance between the skirt and the surface robot is moving on is mentioned to be between 5.3 to 1.8 millimeters, which indicates the surface has to be rather smooth even if the skirt is flexible.

Despite there being multiple different examples of wall-climbing robots implemented with different techniques, the large sucker robot by Nishi presents the two main features which are required from every wall-climbing robot. These are the adhesion and locomotion systems. In this example the whole robot body acts as a suction chamber for the small fan on top. The locomotion uses tracks which ensure large contact area on relatively smooth surfaces.

2.1 Adhesion

Due to the gravity, being able to stay still and move on vertical surface is a challenge. There are multiple different methods developed and used to counter the downward pulling force of the gravity. Depending on author, these can be divided in few different categories. For example, Dethe & Jaju [11] propose categories which are magnetic, pneumatic, mechanical grippers, electrostatic and chemical adhesion systems. Of these, the first three are the most popular choices [1].

To minimize the force required from the adhesion system and in order to carry heavy payloads wall-climbing robots should be as light as possible. In practice [7][15][31] the robots might weight tens of kilos while their payload capability is fraction of that. For example, a robot built to inspect nuclear plants weights 30kg while being able to carry 10kg [7] or MultiTrack has weight of 70kg with 15kg payload capability [18]. Balancing between the robot's dimensions and the payload capability would seem to be problematic. Different adhesion methods affect the robot's weight and size differently, but from use cases and designs presented in literature, each adhesion method can be assumed to have their pros and cons.

While being able to carry relatively heavy loads as mentioned in literature [31], the downside of magnetic adhesion is the fact that it requires ferromagnetic surface to climb on. The weight of magnets increases the weight of the robot, yet they may have high payload capability, as seen for example in robot presented by Yan et al. [31]; magnetic crawler units weight 0.35kg a piece while having absorption force of 18kg. Only some of the magnets are in contact with the surface at given time, and therefore the rest can be considered as dead weight. Yan et al. also mention fragility of permanent magnets and difficulty of detaching the robot from walls as a problems of magnetic solution.

Mechanical grippers may not work on smooth surfaces as their adhesion is based on the gripping element that typically uses hand-like mechanism to grab the surface robot is climbing on. These mechanisms are mainly suitable for different beams and columns according to Kolhalkar and Patil [20]. In suitable environment mechanical grippers might be very effective solution as the adhesion can be achieved with strong mechanical solutions. However, their limitations regarding different surfaces and structures restrict the possible use cases significantly.

According to Dethe & Jaju [11] both electrostatic and chemical solutions were still on development state in 2014. These might offer some lightweight and flexible solution possibilities as the development work goes ahead. One of the problems mentioned by Dethe & Jaju is the fact that some sticky materials used for adhesion would require constant cleaning. However, this might be a problem for other friction-based solutions as well.

Pneumatic solutions are usually based on suction. These can be often quite lightweight, but their traversing ability on rough surfaces is limited due to the leakages, which may lead to loss of adhesion [11]. The suction force is either induced with traditional suction cups or with airflow creating a low-pressure area and therefore making the robot structure to act similar to suction cups. Traditional suction cups are able to induce a force only when static and when the edges are sealed sufficiently, therefore they are mainly used in legged robots such as W-Climbot [15] or in some tracked vehicles as MultiTrack [18], where the tracks consist of multiple suction cups. Solutions based on suction created by high velocity air flow may be used with different locomotion methods as seen in literature [24][28]. However the ground clearance is often quite small as seen with the examples, the large sucker bot has ground clearance from 1.8 to 5.3mm and Ibex 7.5mm. Thrust based solutions seem to be more rare, but some have been presented [5][24]. The ground clearance isn’t as significant design feature in these examples as with suction-based robots, as the adhesion force isn’t based on it. However, the payload capability may be lower, as in the example presented by Nishi the weight of robot is 20kg while the payload capability is only 2kg and wind conditions are mentioned as possible problem.

Overall in wheeled or tracked wall-climbing robots, sufficient adhesion may be harder to ensure and achieve. The adhesion is often based on for example suction or magnetic devices and thereby requiring the robot body to be in close contact with the surface as seen in multiple examples [24][28][33]. The robots have rigid structure and therefore allow very little difference between the contact points between the robot and surface, such as wheels or tracks, without compromising the effectivity of the adhesion method. Solutions like these are capable of crossing small gaps and may be able to move on plastered surfaces, however they may end up losing the grip if trying to cross larger obstacles. There are also examples of tracked robots capable of moving in difficult terrain and between angled surfaces, such as the MultiTrack platform presented by Lee et al. [18]. However, such robots could be considered even more complicated than some of the legged examples.

Limitations set by the surface materials may limit the use of wall-climbing robots. Many examples [1][24][30][31][33] may have problems for example in floor to wall or wall to roof transitions due to the design being based on tight contact with the surface robot is moving on. Devices like these may not be able to work outside built environment as they require certain measures to be taken in order to operate on vertical surfaces. Out of the adhesion methods discussed, pneumatic solutions seem the most versatile. However electrostatic and chemical solutions might offer interesting possibilities in future.

2.2 Locomotion

The locomotion in wall-climbing robots can be divided in several main categories as well, which are tracks, wheels and legged robots. Both tracked crawler type robots and robots with wheels can move relatively fast, but depending on the method used for adhesion, they may not be able to traverse in rough terrains. Generally, legged robots can easily cope with different obstacles, but they require complex control systems and tend to be slow.[11]

Despite Dethe & Jaju [11] consider wheeled and tracked wall-climbing robots relatively fast, depending on the adhesion method and operating purpose some of these may have rather limited speed as well; e.g. the MultiTrack is capable of moving 0.05m/s [18]. The robot consists of multiple tracks with suction cups to ensure the adhesion and thus has rather complex structure, which might be the reason limiting the top speed.

As many examples of wheeled or tracked wall-climbing robots are based on magnetic adhesion or pneumatic suction, they require close contact with the surface they are moving on. Their traversing capabilities on rough surfaces are limited and therefore rigid chassis designs can be used, and no suspension is required. In order to maintain traction and sufficient torque in the locomotion system, the tracks or wheels should be in contact with the surface. This may be problematic in rough terrain if rigid chassis structure is used.

While on typical land vehicles tracks may offer significant benefits over wheels when moving in rough or soft terrain, such properties may not be needed in wall-climbing robots. The main differences in wall-climbing robots are in contact surface, steering and drivetrain, which may be simpler when compared to wheeled robots. Tracks can be also used as part of the adhesion system as seen in some examples [31][33]. However due to the scale of robots, wheels are more likely to be commercially available in sizes needed due to their uses in other applications like radio controlled (RC) cars.

Some legged robots, such as W-Climbot [15], are capable of crossing obstacles and moving between angled surfaces due to their multiple degrees of freedom, while some smaller examples such as Geckobot [30] are limited to flat surfaces. Even if legged wall-climbing robots might have reasonable traversing capabilities, they can be considered rather slow [15][24][11]. W-Climbot has maximum speed of 0.0367m/s [15] and Geckobot 0.06m/s [30]. These are also often based on suction cups and therefore have limitations regarding the surfaces they can move on i.e. they are restricted to smooth surfaces only. As the structure may be higher than in wheeled or tracked robots due to the trajectories needed for walking motion, the adhesion has to be sturdy in order to withstand the torque caused by the mass of the robot.

2.3 Recent wheeled examples

Ibex is sold by Rovertech. It is a simple wall-climbing robot, which relies on suction. The robot has a fan in middle of the chassis creating a lower pressure underside very similarly to the large sucker robot seen in Figure 4. The pressure difference between the underside and the upper side of the robot acts similarly to a suction cup and generates a force towards the surface the robot is driving on. The Ibex robot can be seen in Figure 5.

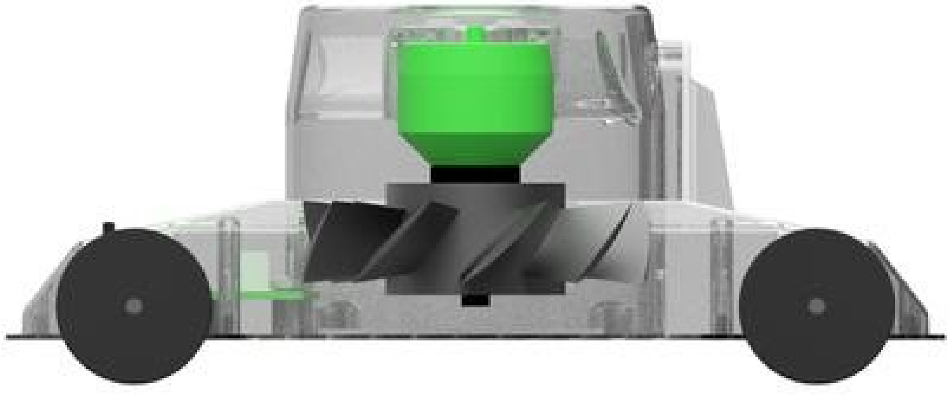

Figure 5. *Ibex wall-climbing robot [28]*

The robot is capable of driving on somewhat uneven surface such as plastered walls and some versions are capable of doing transitions between horizontal and vertical surfaces. However, the 7.5mm ground clearance and rigid carbon fiber chassis structure does set limitations on the objects the robot can pass and large gap between the chassis and the surface might set the robot to a risk of losing traction due to the pressure rise on the underside of the vehicle. The robot is fully relying on operator control in all functions including the suction fan speed [29].

VertiGo is a wall-climbing robot developed in collaboration between ETH Zurich and Disney Research. The robot is theoretically capable of moving on surfaces of any angle and even on uneven surface. The VertiGo wall-climbing robot can be seen in Figure 6.

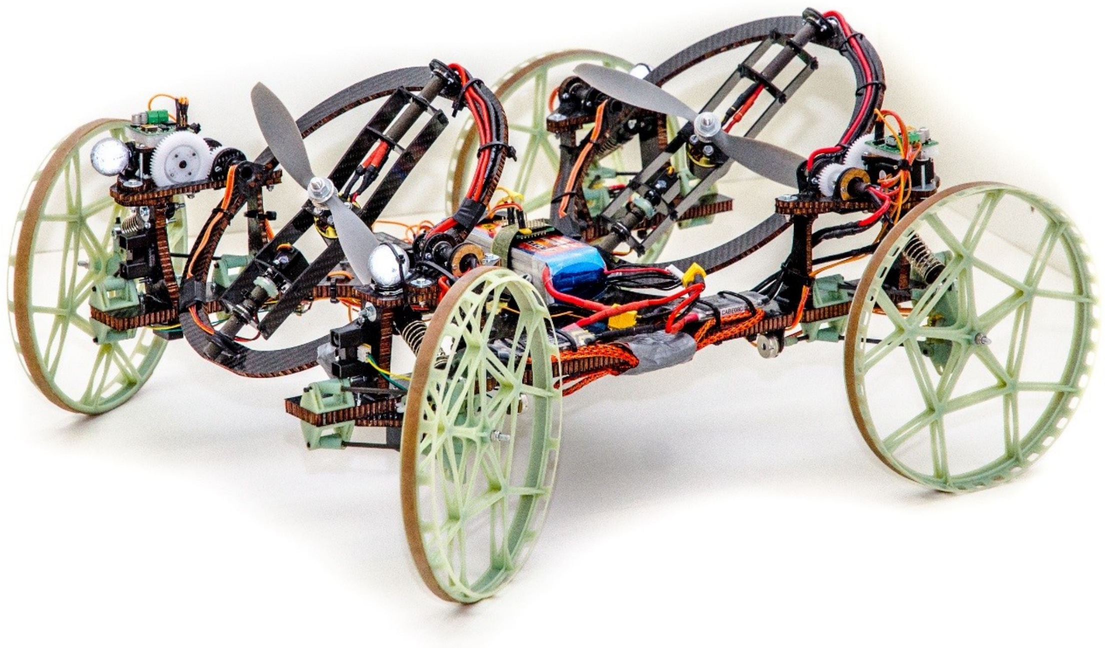

Figure 6. *VertiGo wall-climbing robot [5]*

While the Ibex relied on suction created by a propeller VertiGo relies on thrust generated by two larger propellers. The robot has no propulsion in its wheels and therefore every movement is done by controlling the thrust generated by the propellers. The wheels are able to turn in order to assist steering.

Due to the large wheels and high ground clearance VertiGo can cross quite big objects. Each wheel is steered and has double wishbone suspension in order to even out some of the surface irregularities. As the robot is controlled by thrust vectoring, the propellers require more complex control system than seen in Ibex. However, some weight has been saved by using carbon fiber structures and using the thrust for propulsion and thus avoiding the need for separate drive motors.

2.4 Drones

Drones are helicopters consisting of multiple propellers and usually bit easier to control than regular helicopter due to more advanced control systems. They are commercially available in almost all sizes and shapes and could therefore be used as a replacement for wall-climbing robots in certain operations, e.g. cleaning of vertical surfaces offered by Cleandrone [9].

Increasing load capacity in drones usually requires either bigger propeller diameter or higher number of propellers. This leads to horizontally larger overall diameter of a drone, which might be problematic in certain use cases or applications requiring close contact with the surface being inspected or operated. Especially with high payloads the drone's overall diameter may increase significantly.

There are also devices developed, which move like a drone, but have also the possibility to attach to walls and move similar to a wall-climbing robot. The robot developed by Myeong et.al. [22] is capable of hovering like a drone, but also moving on a vertical surface with wheels. This kind of structure might be very versatile in places with enough space to fly and hover around. However, the robot has only 90% success rate on sticking to the wall and there is no information about whether the robot is capable of sticking to other than vertical surfaces. Further research and development would be required in order to surpass wall-climbing robots on all possible inclined surfaces.

The main effective differences in drones and wall-climbing robots are the shape and size, and the way they work and operate. As drones are fully based on propeller thrust, subtle movements may be more difficult than in wall-climbing robot resembling RC car. However, the difficulty of controlling the device is highly dependent on the device, component quality and possible additional assisting devices and methods.

3. PNEUMATIC ADHESION AND OTHER TECHNICAL SOLUTIONS

Pneumatic adhesion systems are based on suction and thrust. The former often offers better grip with same amount of power but is also dependent on the robot ground clearance or surface smoothness. In order to achieve similar gripping force with thrust, more power is required, but the ground clearance is not limited in similar way as with suction.

These two methods can be also used simultaneously, though the suction will be the dictating the robot ground clearance. Such system is described by Z. Jiang et al. in their conference paper “Study on pneumatic wall climbing robot adhesion principle and suction control” [27]. This is actually the system used in Ibex wall-climbing robot [28], even though the adhesion force gained by thrust in that case is minimal. The propeller used is small compared to overall area covered by the robot and therefore the thrust produced is negligible compared to the suction induced by the airflow through the 7.5mm ground clearance.

3.1 Suction

As there is a pressure difference between the sides of the suction cup, it will lead to adhesion force that is proportional to the pressure difference and area covered by the suction cup. The force is generated according to formula:

$$\boldsymbol{F} = \boldsymbol{\Delta p} \cdot \boldsymbol{A} , \tag{1}$$

where the F is the force towards the surface suction cup is sticking to, Δp the pressure difference and A the surface area of the low pressure under the suction cup. Principle of suction cup is presented in Figure 7.

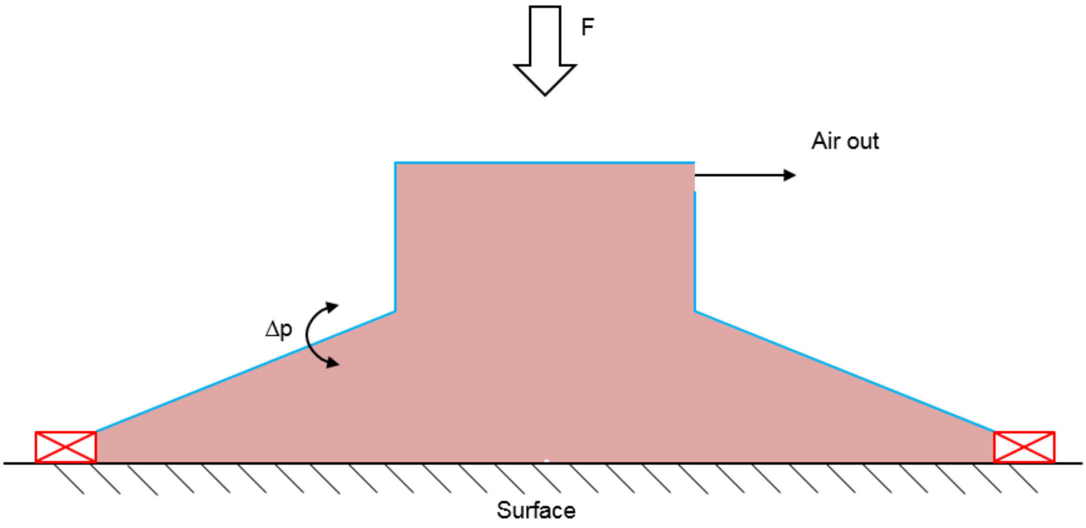

Figure 7. *Suction cup cross-section and operating principle*

The edges, presented with red boxes in Figure 7, should be sealed tightly, while the air under the cup, presented with blue, is removed. Removing the air under the cup will create an area with lower pressure, presented with red, and therefore a pressure difference between the different sides of the suction cup. The air pressure is affecting the whole outer surface of a suction cup and an adhesion force is achieved according the equation (1).

As suction cups require the gap between the surface and the cup to be sealed in order to function reasonably, they cannot be moved without lifting the cup and losing the suction effect, unless the surface is perfectly smooth. Their use in a robot that uses wheels and rocker-bogie suspension for traversing would require complex mechanical solutions. Either the suction cups should be integrated to the wheels similar to Waalbot by Unver, Murphy and Sitti [30] or they would require mechanical actuators to move them around similar to legged robots such as W-Climbot [15]. The latter solution would render the wheels inadequate during climbing, as it would be easier to implement all of the movement and support from the wall with actuators used to move the suction cups, yet this has already been done multiple times.

Instead of removing some of the air in certain space, the lower pressure required to achieve suction can be also created according to the Venturi effect, which is a derivative from Bernoulli equation:

$$\boldsymbol{p + \rho g h + \frac{1}{2}\rho v^2 = constant}\ , \tag{2}$$

where p is pressure, ρ the density of air, g acceleration due to gravity, h height of the flow area and v the flow velocity. Pressure difference created by Venturi effect can be presented as:

$$\Delta p = \frac{\rho}{2} \cdot (v_2^2 - v_1^2) \, , \tag{3}$$

where Δp is the pressure difference, ρ the density of air, v_2 the velocity of fluid in narrow gap and v_1 the velocity of fluid in wider gap. The principle of suction device based on Venturi effect is presented in Figure 8 as a cross-section of a device creating the suction force.

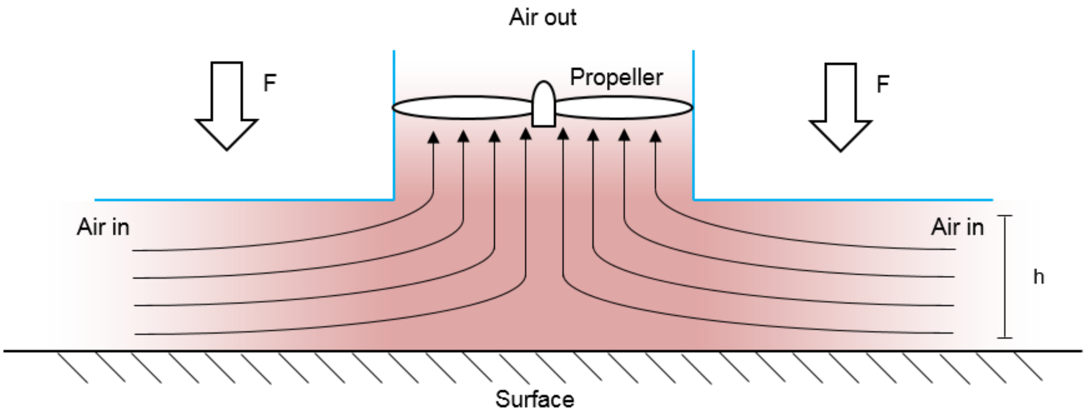

Figure 8. *Low pressure generated due to larger velocity of a fluid*

In subsonic speeds air can be considered as an incompressible fluid [12] and therefore the mass flow would be almost a constant. This would cause higher flow speeds in narrower sections of the channel the air flows through. In Figure 8, if a propeller would suck the air under the blue structure, the velocity of air would rise in red areas according the equation (3). Unlike the suction cup, where the air pressure is affecting the whole cup, in suction device based on Venturi effect the air pressure only affects the edges of the device and not the area where the air is led out. However, depending on the method used to cause the rise in air velocity, in addition to suction on sides, some thrust could be induced in middle where the air is coming out of the device.

The Venturi effect presented in equation (3) does not insist the air to flow in certain direction. The lower pressure can be achieved by either sucking the air through the gap as illustrated in Figure 8 or by pushing the air through the gap as presented by Erzincanli, Sharp and Erhal [13]. Pushing the air sets certain limitations, as high airflow towards the surface might cause the pressure to rise under the device instead of causing a low-pressure area.

In order to achieve stable and even airflow through the gap, the airflow can be directed sideways. Rotating motion can be used as proposed by Li, Kawashima and Kagawa [19]. This is done in order to decrease the required mass flow [19] and not to disturb the airflow significantly when it comes in contact with the surface, so the pressure shouldn't rise under the suction device like in Bernoulli levitation grippers [10]. Adhesion devices using circular flow are called vortex grippers. The principle is illustrated in Figure 9.

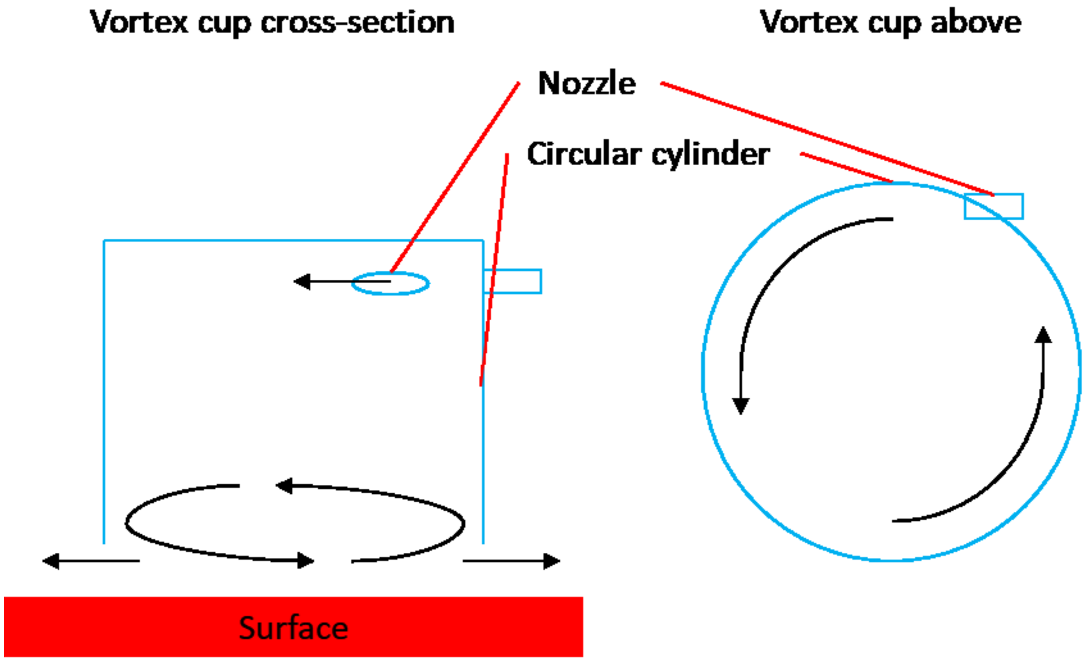

Figure 9. *Airflow in vortex gripper*

The airflow is directed in circling vortex. The air will escape through the small gap between the device and the surface as seen in Figure 9. The air velocity will rise in this gap and therefore cause low-pressure zone according to the Bernoulli equation (2) and Venturi effect (3). Air pressure outside the vortex cup will push the gripper towards surface according the equation (1), similar to suction cups.

This kind of devices are mainly used in industry as non-contact grippers in applications where delicate handling is required. The adhesion force of vortex gripper is dependent on the gap size between the gripper and surface the gripper is sticking to [19]. This could be also deducted from equation (3) as the air flow velocity is dependent on gap area, assuming the mass flow rate is equal.

While the vortex gripper and Bernoulli levitation are interesting concepts, they have been mainly used in industrial gripping purposes. The concepts presented in literature [10][13][19] have been only tested with very close proximities between the gripper and surface being handled. For example, Li, Kawashima and Kagawa studied gap heights of 0.08mm to 1.00mm in their tests [19]. The gap in a wall-climbing rocker-bogie robot should be considerably larger, which might be possible with higher air flow rate, as the air velocity, and therefore suction force achieved, is dependent on the gap height or air mass flow rate.

3.2 Thrust

Thrust is the method used to cause the forward motion in airplanes and lift in helicopters. There are different ways to generate thrust, but the simplest is probably a rotating propeller. Other common methods to generate thrust in addition to propellers are different turbine and jet engines. In some variants of these, such as turbofans and turboprops, some of the thrust is generated by rotating propeller, but some of the thrust is also generated by the pressure increase caused by the jet fuel combustion.

In wall-climbing robots, thrust can be either directed statically towards the driving surface, or it can be dynamically directed in the most optimal direction. If direction is dynamic, it should be determined in a way it creates friction great enough to allow robot to move, yet mainly focus working against gravity and therefore allowing the force to be as low as possible. This method is discussed further in chapter 3.2.1.

On tilted surfaces where force generated by friction is not enough to keep the robot in place, the adhesion can be increased by increasing the force towards the surface and the thrust direction can be static. This increases normal force of the surface and therefore the friction between the robot and the surface. Friction is a result of the normal force of the surface and friction coefficient as seen in equation

$$\boldsymbol{F_f} \leq \boldsymbol{\mu} \cdot \boldsymbol{F_n}\,, \tag{4}$$

where F_f is the maximum force generated by friction, μ the friction coefficient and F_n the normal force of the surface. The friction coefficient is less than 1 between most materials, and therefore the force required to keep the robot on inclined surface will be greater than what would be required to lift the robot to air.

As the force ensued by the acceleration of the robot and the friction coefficient between the wheels and surface are known, it is possible to calculate the minimum friction force required between the robot wheels and the surface when the robot is accelerating. The amount of force generated by friction should be always this or more.

3.2.1 Thrust vectoring

Thrust vectoring means controlling the direction of the force generated by the thrust. It is regularly used in rocket-powered devices, such as spacecraft and missiles, but also on some aircrafts like airships, tiltrotors and fighter jets.

The idea of thrust vectoring in a wall-climbing robot would be generating sufficient force to override the effects of the gravitation and to generate a normal force with the surface that is capable yielding enough friction for the robot to move. As most of the force goes straight towards countering the effects of gravity instead of generating friction force, the required force will be lower than when the thrust is only directed towards the surface robot is moving on. This is due to the friction coefficient that often reduces the efficiency of thrust directed towards the surface.

In practice the weight would be most likely higher on a wall-climbing robot capable of thrust vectoring, than in a wall-climbing robot with static thruster or drone, as thrust vectoring requires additional control actuators and support structures for the device generating the thrust. The thrust producing component, e.g. a propeller, should have at least two degrees of freedom to be able to direct the thrust in every situation despite the robot orientation. Movement boundaries should be rather large in order to guarantee correct thrust vector angles. This dictates the placement of all the other components of the robot, as the space reservation of the thrust source would be significant. All the other components should be also placed in a way they won't disrupt the thrust.

3.3 Propeller thrust

Propeller rotated by an electric motor is the most suitable method of producing thrust in a small robot using electric power. The exact details of the way propeller generates thrust are complex, but simplified momentum theorem can be used and propeller can be presented as a disc [23] as seen in Figure 10.

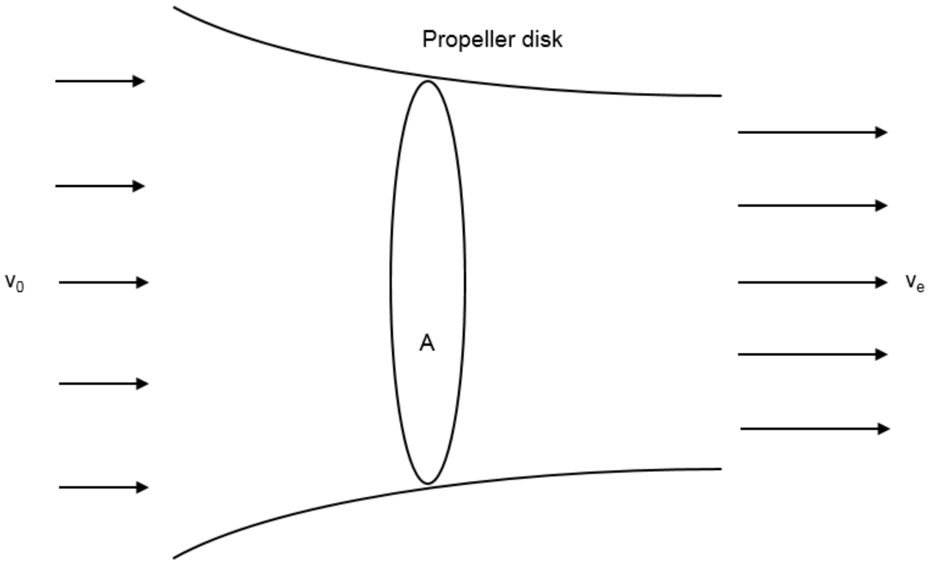

Figure 10. *Propeller thrust*

According to NASA [23] thrust can be estimated with simplified momentum theorem leading to equation:

$$\boldsymbol{F_t} = \frac{1}{2} \cdot \boldsymbol{\rho} \cdot \boldsymbol{A} \cdot (\boldsymbol{v_e^2} - \boldsymbol{v_0^2}), \tag{5}$$

where F_t is the thrust, ρ is the density of air, A is the area of propeller disk, v_e the air speed behind the propeller and v_0 the air speed in front of the propeller. As the propeller is used to generate thrust to keep the robot on wall, it won't move on significant speeds in relation to the air around. Therefore, the air speed in front of the propeller can be taken as 0.

As propeller blades are like rotating wings, in practice the area of single propeller blade creates the thrust instead of the whole propeller disc area. Exact calculations would be relatively more complex and therefore not represented here as the simplified equation with propeller disk should offer good enough generalization. With simplified theory where the propeller is considered as a simple disc, only the propeller diameter is affecting the total area used in calculations.

The number of blades doesn't have direct effect even if more complex and accurate theory would be used, as same total area can be achieved with fewer blades as well. The downside of multiple blades is increased disturbance in air around the propeller, which causes turbulence and therefore loss in efficiency. [12]

Propeller pitch is usually given in inches and means the distance the propeller is supposed to move forwards each turn. As the propeller won't be able to move through the air is case of a wall-climbing robot, the air velocity behind the propeller can be assumed to be somewhat correlating with the propeller pitch, which can be expressed with equation:

$$\boldsymbol{v_e = s_{pitch} \cdot \omega}, \tag{6}$$

where s_{pitch} is the propeller pitch and ω the rotational speed of the propeller, all in SI units. In practice the propellers have certain amount of slipping, and thus won't actually move the distance suggested by the pitch. However, the amount of slipping is unknown.

It can be deducted from the equations (5) and (6) that the thrust is depending on the propeller area and the velocity of the air, therefore the propeller diameter and pitch. In order to achieve certain thrust either large propeller on slow rotational speed can be used or smaller propeller but with higher rotational speed assuming the pitch is the same. If the rotational speed would be the same a large propeller with small pitch could produce similar thrust to smaller propeller with larger pitch.

However according to Anderson and Eberhardt [12], it is more efficient to accelerate larger quantities of air at low velocities, rather than smaller quantities at high velocity. The kinetic energy left in the air behind the thrust source means wasted energy. This can be also seen in some commercial products. Small electric ducted fans (EDF) tend to require quite high voltages and current, thus power, to achieve similar thrust that is promised for certain larger motors meant for big propellers.

3.4 Propeller ducting

As propeller blades cut through the air they create turbulence in the air near the blade tips similar to plane wings. High pressure air under the blade may flow to the upper surface leading to loss of efficiency [12]. This flow appears mainly outside the propeller diameter as presented in Figure 11 and thus isolating the propeller from the surrounding air volume the flow can be minimized.

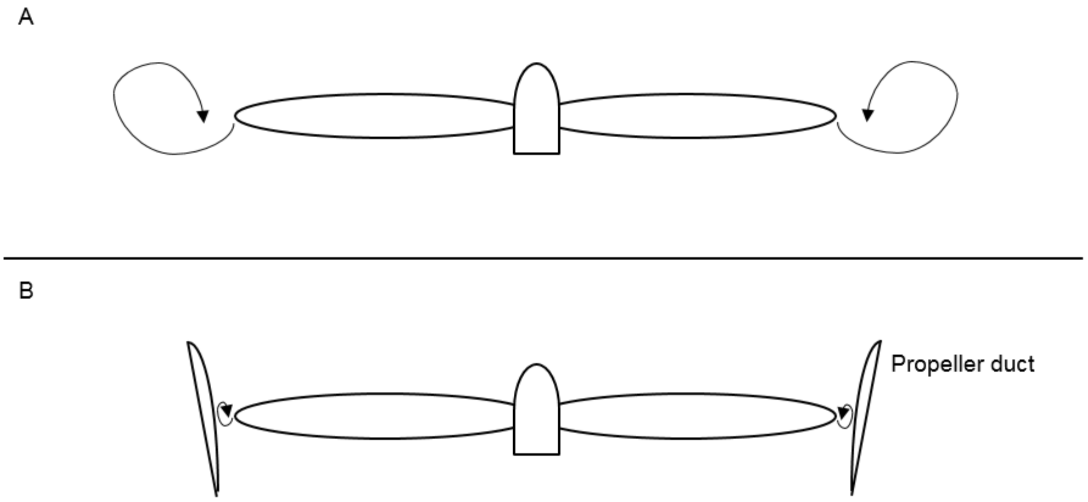

Figure 11. *Turbulence at propeller tips with (B) and without (A) a duct*

As presented in Figure 11 b while there is very little to no air right around the propeller blade tips the flow from lower surface to upper surface can be minimized.

Some of this turbulence can be addressed with the propeller tip design. For example, so called bullnose design may create higher thrust due to larger surface area of the propeller, but it will create higher turbulence and increase drag. Regular propellers compromise some thrust with tapering tips, while increasing efficiency, but even tapering tips create turbulence and drag. One possibility is to use so called Q-tip propeller where the propeller tip is turned upwards, thus creating a virtual ducting around the propeller. Similar design to propeller Q-tips is used in the winglets of many passenger airplanes.

While reducing the turbulence and drag, propeller ducting can be theoretically also used to increase the thrust from propeller. As presented by NASA [23], a propeller is sucking the air from larger area than the propeller disk area. The air going through the propeller will have higher velocity than the static air around, and thus according to the Bernoulli equation and Venturi effect presented in equations (2) and (3) should have lower pressure. Specially shaped intake duct seen in Figure 12 should increase the propeller thrust.

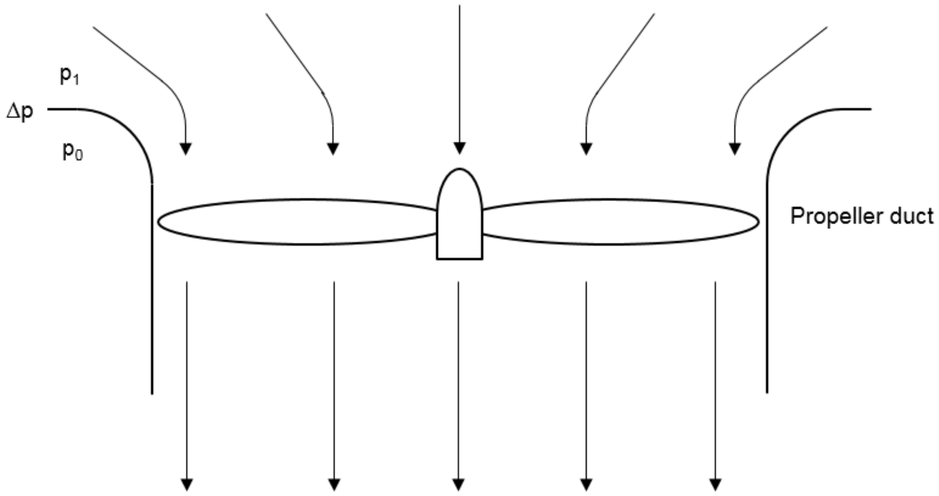

Figure 12. *Intake duct shape*

The rounded edge of duct should allow better air intake closer to the duct, and therefore increase the air flow above the duct. As the air pressure above the duct lip is lower according to the equations (2) and (3), there will be pressure difference over the lip and therefore a force generated according to the equation (1).

Above-mentioned principle should work in midair, but the effect should be even greater if the ducting is near a surface, so the air has to flow through a narrow gap between the surface and the duct. The smaller the gap the higher the flow, as presented in chapter 3.1 and Figure 8.

If designed incorrectly, adding structures near the propeller flow might also cause contrary effect and increase the drag. Defining the effects of each structure is really difficult without complicated and time-consuming simulations, thus more practical approach of testing parts in practice will be chosen for this purpose.

3.5 Other additional methods

The main problem the adhesion device is trying to solve, is countering the impact of gravity. It is possible to limit the impact with special design solutions, that won’t affect the way adhesion method works, but reduce the force required from it.

The simplest solution is to keep the weight of the robot as low as possible. With intelligent design it is possible to reduce the weight of the robot chassis. Used materials and manufacturing methods will also have an effect to the total weight of the robot. This will be an important design consideration for a wall-climbing robot.

A passive system, such as structures filled with gas lighter than air, would reduce the impact of gravity as well without increasing the total mass of the robot too much. This method is commonly used in hot air balloons and airships. It is based on buoyancy, which can be calculated with the equation:

$$\boldsymbol{F_b = \rho \cdot g \cdot V}, \tag{7}$$

where F_b is the force caused by buoyancy and V the volume of the light gas or fluid replacing heavier gas or fluid. As stated in equation (7) the buoyancy is linearly correlating with the volume of the gas or fluid replaced. In order to calculate the total effect of such passive device, the weight of the light gas has to be taken in account. The total force of such device would be:

$$\boldsymbol{F = F_b - m_{gas} \cdot g}, \tag{8}$$

where F is the total force and m_{gas} the mass of the light gas.

To reduce the weight of a 1kg robot to half, it would require almost 500 liters of helium or alternatively approximately 455 liters of hydrogen. As the buoyancy is only correlating with the volume of the fluid or gas replaced, pressurizing the gas won't affect the result positively. Volumes of this size would increase the size of the robot significantly and thus any buoyancy-based devices may be considered as futile.

3.6 Rocker-bogie suspension

Some sources, e.g. [8], state the rocker bogie suspension should be able to pass obstacles up to twice the size of a wheel diameter. In practice this ability is highly dependent on ground clearance below the robot's body and the geometry of rocker and bogie.

One of the biggest benefits of the structure is the ability to keep all or most of the wheels in contact with the surface the robot is moving on, in almost all situations. This is done without additional suspension components, such as springs. This might increase the lifespan of the system as there are less components prone to breaking or malfunctioning.

There are two major things to be considered in the rocker-bogie suspension structure. As the suspension is connected to the main chassis with revolute joints, the other major consideration is keeping the chassis level. The other one is steering as the structure has usually at least six wheels.

3.6.1 Averaging mechanism

In a robot utilizing rocker-bogie suspension the body of the robot is hanging between the left and right rocker, which are attached to the body by rotational joints as seen in Figure 3. Without any control between the rockers and the body, the body could freely swing between the rockers. This might cause unnecessary stress to certain parts such as wires between the body and the rockers when the body rotates, or the body might hit some obstacles.

The body leveling control can be done either purely mechanically or with additional actuators and based on measurement and control logic. The latter might offer some additional possibilities as the orientation of the body would have better adjustability, but it would also add more complexity to the system. As the main purpose is to keep the body nearly parallel to the surface the robot is moving on, mechanical solutions are sufficient.

There are two main mechanical designs used in rocker-bogie suspension to control the level of the body. The other one is similar to differential in cars connecting the rockers with axles and gears, while the other utilizes different linkages between them.

The differential system, seen in Figure 13, can be implemented in quite small space, but unless some additional systems, e.g. complex gearing or linkages, are used, this space has to be between the rockers. The robots body acts as differential housing and as one of the rockers rotates it either forces the other rocker to rotate in opposite direction or the body to rotate half of the angle the rocker rotated.

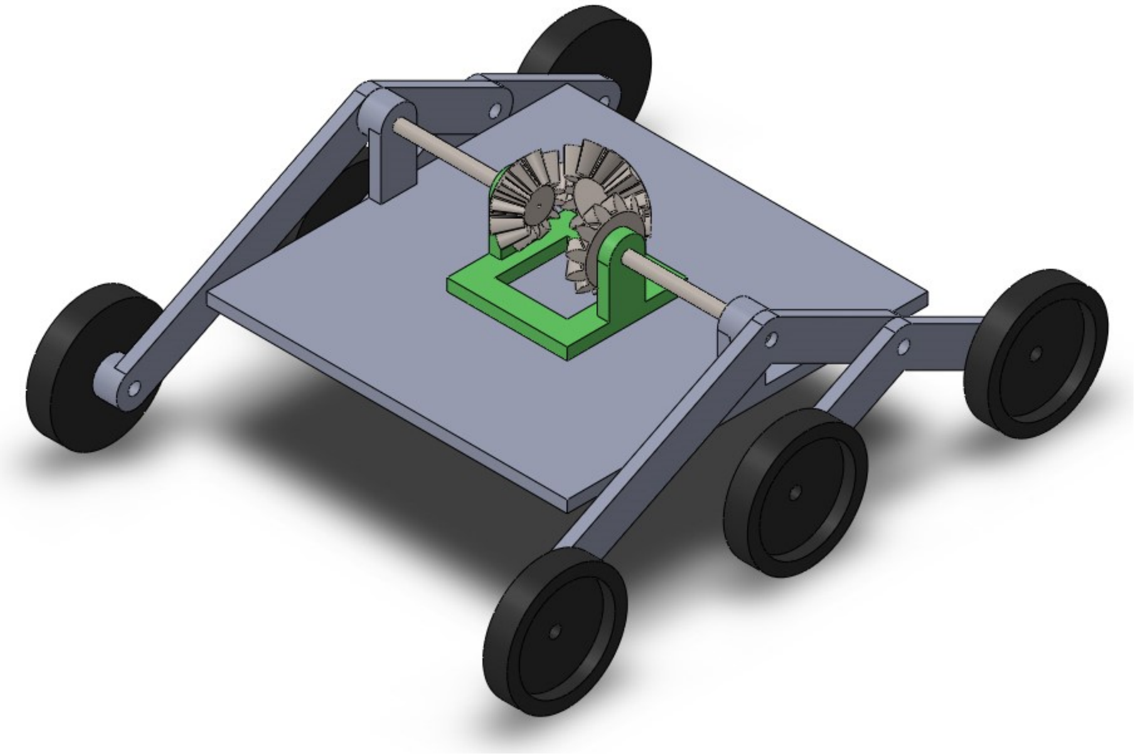

Figure 13. *Rocker-bogie suspension with differential averaging mechanism*

In linkage system the connection between the rockers is done with linkage bars, which are interconnected either with a single bar or with set of links and arms connected to robot’s body. While the implementation is different from the differential system, the functionality is exactly the same; the tilt angle of the robot’s body shall remain as half of the angle difference of the rockers. A simple version of linkage system is presented in Figure 14.

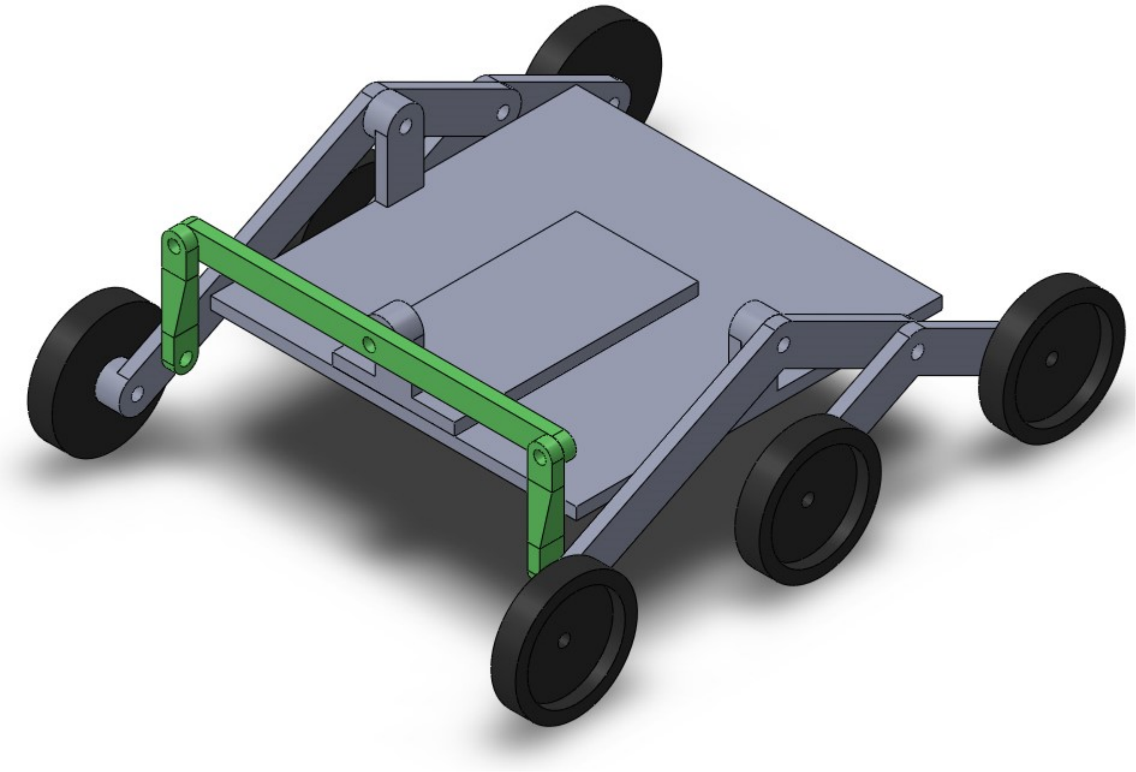

Figure 14. *Rocker-bogie suspension with linkage averaging mechanism*

The averaging mechanism based on linkages, presented with green in Figure 14, is more suitable for a wall-climbing robot using adhesion method not tied to the locomotion. The source of adhesion can be placed more freely in the middle of the robot, unlike in differential solution where the differential reserves the space in the middle.

3.6.2 Steering

As a rocker-bogie robot is wheeled vehicle, there are two different options for the steering system. These are steering by turning the wheels around their vertical axis and differential steering mechanism.

Differential steering means rotating the wheels either on different speeds or in different directions. Depending on the speeds and directions in which the wheels are rotating, the system may be capable of tight turning radiuses. However, the wheels can’t follow their optimal paths of travel while the vehicle is turning, which causes a lot of stress to the robot structure and additional forces between the wheels and the surface the robot is driving on. This might be problematic while driving on surfaces with low friction coefficients as loss of friction might affect the robot’s ability to accelerate or in worst case lead to uncontrolled sliding or falling.

Turning the wheels around their vertical axis allows the wheels to move along the optimal path and therefore reduce the stress in robot structure and unnecessary forces between the wheels and the surface. However, in case of 6 wheeled vehicle, such as rocker-bogie robot at least four of the six wheels require additional steering motors. These can either be at one end and middle wheels, i.e. front and middle wheels, or at both ends, i.e. front and rear wheels.

Both systems have their pros and cons. Here traditional steering with turning wheels was chosen due to better steering properties. It also appears to be common for example in mars rovers developed by NASA. Even though the steering motors may add some weight, the robot chassis may be lighter than what would be required from a robot with differential steering, as there should be fewer lateral forces.

4. REQUIREMENTS FOR WALL-CLIMBING ROBOT WITH GOOD TRAVERSING ABILITIES

This chapter aims to define requirements seen as the most important for a wall-climbing robot with good terrain traversing capabilities. These requirements are partially defined based on the features and defects seen in literature presented in chapter 2 and partially based on the limitations, requirements or possibilities set for this thesis work.

Some of the requirements can be seen as general requirements applying to all or most wall-climbing robots. While some are more specific for this particular development work. As there are certain limitations and requirements set for the development work and design decisions made, some of the requirements may already be considered or defined as uniform for all concepts that will be discussed in chapter 5 and therefore rendered unnecessary.

4.1 General requirements

- **Required adhesion force**

As wall-climbing robots should be capable of moving on vertical surfaces, one of the most important requirements is the capability of staying on surface reliably. Depending on how the adhesion method is implemented, different amounts of force may be required in order to be able to move on surface. If different methods are used, they may have different power requirements.

The amount of required adhesion force will also affect other properties of the robot. If a propeller is used as a part of the adhesion system, lower thrust requirement enables either smaller propeller size or lower propeller speed, as can be seen from equations (5) and (6),. Both can be considered as wanted features.

In addition to adhesion method implementation there are also other properties affecting the required adhesion force. The main factors are robot weight and friction coefficient between the wheels and the surface robot is moving on. As the surface material and possible dust or particles between the surface and the robot will in most cases affect the required force, an absolute force value is difficult to define. However, required force on some predefined surface can be used as an indicator to compare the adhesion methods, e.g. for this development task static friction coefficients of 0.5 to 0.75 were measured between the wheels used in the robot and inclined surface used for testing. Different concepts can be compared based on this information.

- **Weight**

As stated in literature [11][20], wall-climbing robots should have low weight and high payload capability. Adhesion systems are capable of inducing certain level of maximum adhesion force and therefore the higher the weight of the robot, the lower the payload capability. The weight will also highly influence the required adhesion force without any payload.

The structure of the robot will highly affect the weight. Used materials, shapes and the chosen design will define the mass of the robot. Some of the mass can be shaved off with intelligent design of individual parts, but also the chosen adhesion method may set some limitations due to required components, shapes or mechanical functionalities.

Due to intended prototyping nature of the robot developed in this thesis, the structure will be mainly 3D-printed. This will set certain limitations to materials and structures used. As most parts share similar manufacturing method, the weight of different concepts can be estimated from the size and amount of required parts. Higher volume of parts will indicate higher weight of the structure. However due to the manufacturing method, exact strength of the parts may be difficult to estimate accurately before actually implementing them, and therefore the most lightweight concepts may end up being too fragile. Knowledge and experience of designer has to be used in estimating process to avoid the need of prototyping every possible concept design.

When considering the weight of additional components, the estimating can be more difficult. Exact weight of different wires and adapters may be impossible to estimate as these values may not be given by the manufacturers. Also, some weight values given by the manufacturers may not be accurate. However, if similar components are used in different concepts, even inaccurate values can be seen as directive.

- **Ability to move on different surfaces**

Ability to move on different surfaces is an important feature for wall-climbing robot without strictly predefined use case and environment. As mentioned in chapter 2, many wall-climbing robots may have problems moving on and between different surfaces. Robots may be designed for rather limited purpose or environment, such as moving only on certain type of wall.

The ability to move on different surfaces can be seen both as an ability to move in an environment with non-flat surfaces and obstacles, as well as to move on different surface materials, such as rough brick wall or smooth glass surface. In case of non-flat surface with obstacles the ability requires the robot structure to be capable of adjusting to different terrain heights and preferably high ground clearance. When different surface materials are considered the robot has to be able to generate sufficient adhesion force which is influenced by the friction coefficient between the robot and the surface.

When crossing obstacles or doing a transition between differently angles surfaces, the locomotion components should be the only parts of the robot to come in contact with the surface. For examples in wheeled robots the wheels should be the first part to hit an obstacle or a wall in order not to get stuck. Also, the adhesion should be capable of keeping the robot in contact with the surfaces when doing a transition between differently inclined surfaces. In many suction-based robots the transition between different surfaces may cause the gap under the robot to grow too large, thus leading the robot to lose some of the adhesion force.

- **Ability to move omnidirectionally**

In order to move to a specified position or to avoid certain difficult obstacles a wall-climbing robot should be able to move omnidirectionally. This requirement concerns mainly the locomotion system in sense of driving and steering but may also place some requirements on the adhesion system depending on the implementation.

As seen in VertiGo [5], if thrust vectoring is used to minimize the adhesion force, the thrust source has to have multiple degrees of freedom. The thrust has to be always pointed in optimal direction in despite the robot's orientation. Then again in more traditional solution where the adhesion force is pointing towards the surface, the ability to move omnidirectionally does not place additional requirements for the adhesion method.

4.2 Additional requirements

- **Ground clearance**

Ground clearance is the main defiance of many wall-climbing robots as stated in chapter 2. They either require completely smooth surface, are able to traverse on mildly rough surfaces e.g. plastered walls, or they may be able to climb over obstacles as long as the surface is relatively smooth around the obstacles.

As the objective is to research possibilities for a wall-climbing robot that would be capable of traversing in rough terrain and over obstacles, this is one of the most important features. The robot shall utilize rocker-bogie suspension and therefore the wheels should be able to climb over quite large obstacles. However, the chassis of the robot shall have high ground clearance as well in order not to get stuck on obstacles. The higher the ground clearance the better.

The prototype robot should have at least 3 to 5cm of ground clearance in order to cope with different terrain variations and obstacles seen in e.g. built office environment. This will most likely affect the robot form and structure. High ground clearance might also affect the effectivity of certain adhesion methods; as seen in literature some adhesion methods require very low ground clearance.

- **Form factor**

Most existing examples utilizing wheels or tracks have low form as seen in examples mentioned in chapter 2. Some of legged robots such as W-Climbot [15] have higher profile but some try to stay close to the surface as seen in MRWALLSPECT - III shown previously in Figure 1.

The surface the robot is moving on is usually the target being either inspected or worked on, and therefore saying close to the surface is also justified. Low profile keeps the center of mass close to the surface, thus minimizing the torque ensued to the locomotion system by the robot weight. Torque could cause additional stress to the structure or possibly decrease the traction in upper parts of the locomotion system.

Overall smaller robot is easier to handle and transport if needed. Large robot in sense of width and length as well as height will most likely also be less versatile as some of the features in the use environment such as narrow passages may limit the robot use. Large dimensions also often are related to higher weight.

- **Simplicity of structure**

A complex structure requires more work hours to design and manufacture and therefore will end up being more expensive to implement. 3D-printing allows using of complex shapes and structures, yet there are certain limitations. As PLA plastic is mainly used as the building material, structural strength has to be also taken in account with complex shapes. This may require avoiding certain structures or adding more material, and therefore weight in order to make the structures strong.

Due to prototyping character of this thesis work simple structure is appreciated. Modifications are easier to do, and new parts can be manufactured faster if defects are detected. But also less time will be wasted on designing possibly faulty parts if the structure is simple.

- **Simplicity of control**

Complexity of the control system needed to control the adhesion system directly affects the resources needed to develop the system. Designing, implementing and testing the system requires time and effort.

More complex system may also require additional actuators which in addition to requiring money and time, to make them work properly, may set more additional requirements or limitations for things like structure and other actuators. Given the limited resources and rather wide scope for this thesis work more complex systems are seen as less desired.

5. DEVELOPMENT OF A CONTROL SYSTEM CONCEPTS

5.1 Determining the required thrust

Possibilities for different pneumatic adhesion methods were presented in chapter 3. Of these regular suction cups and vortex grippers can be ignored. Suction cups would unnecessarily complicate the structure of a wheeled robot, and while vortex gripper is an interesting idea, it would most likely require external compressor for sufficient airflow while similar thrust and suction based on Venturi effect seen in Figure 8 can be achieved with simple propeller.

The force required from static propeller or thrust vectoring can be estimated with calculations. As the robot is moving over relatively horizontal surface, force isn’t required as gravity will generate enough friction to move. Thus, it is important to define maximum climbing angle where additional force won’t be needed. This can be done with the free body diagram seen in Figure 15.

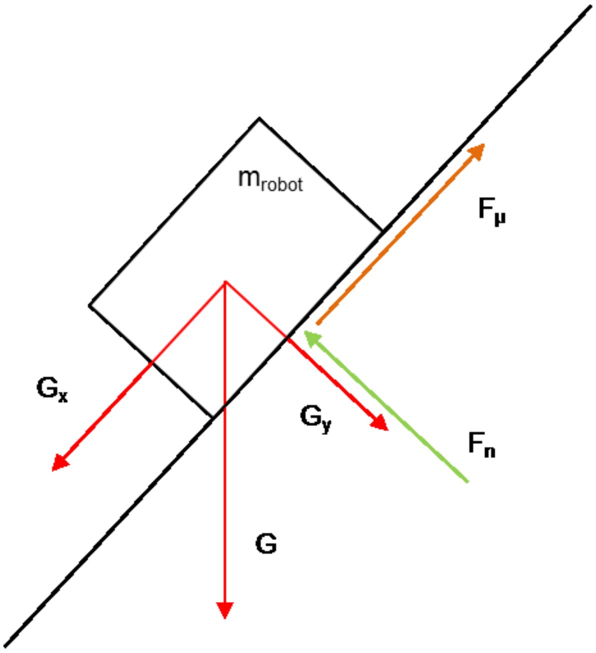

Figure 15. *Free body diagram of the rocker-bogie robot on an inclining surface*

The friction force has to be equal to the component of gravitation force G parallel to the surface. Maximum friction force is the component of G towards the surface multiplied by the friction coefficient, as stated by the equation (4).

As already stated in chapter 3.2, in order the robot to be able to move, the maximum friction force has to be always high enough to provide some friction as the motors accelerate. Friction force required for the robot to accelerate can be calculated if maximum acceleration and friction coefficient between the wheels and the surface is known, according to equation:

$$\boldsymbol{F_{f\,acc} = \frac{m_{robot} \cdot a_{robot}}{\mu}}, \tag{9}$$

where $F_{f\,acc}$ is the minimum normal force required to accelerate, m_{robot} the mass of the robot, a_{robot} the maximum acceleration and μ the friction coefficient. With the force from equation (9) and free body diagram in Figure 15, it is possible to deduct the maximum inclination angle the robot will be able to climb without any extra support. The information can be combined into function:

$$\boldsymbol{G_x = G_y \cdot \mu - F_{f\,acc}}, \tag{10}$$

where G_x and G_y are the components of the gravitational force G. Components G_x and G_y can be calculated with simple trigonometry:

$$\boldsymbol{G_x = G \cdot sin(\alpha)}, \tag{11}$$

and:

$$\boldsymbol{G_y = G \cdot cos(\alpha)}, \tag{12}$$

where α is the inclination angle. The maximum climbing angle α can be found by finding the maximums of function (10). As all relevant forces are dependent on the mass, the only value affecting the maximum climb angle is the friction coefficient μ. Assuming the friction coefficient is 0.75, the maximum climbing angle would be 30.625 degrees. After this angle the robot requires additional adhesion methods to be used, i.e. the propeller has to be turned on to produce thrust or suction.

5.1.1 Static thrust

As explained in chapter 3, with static thruster, the thrust is always directing towards the surface the robot is moving on. The free body diagram of the situation is presented in Figure 16.

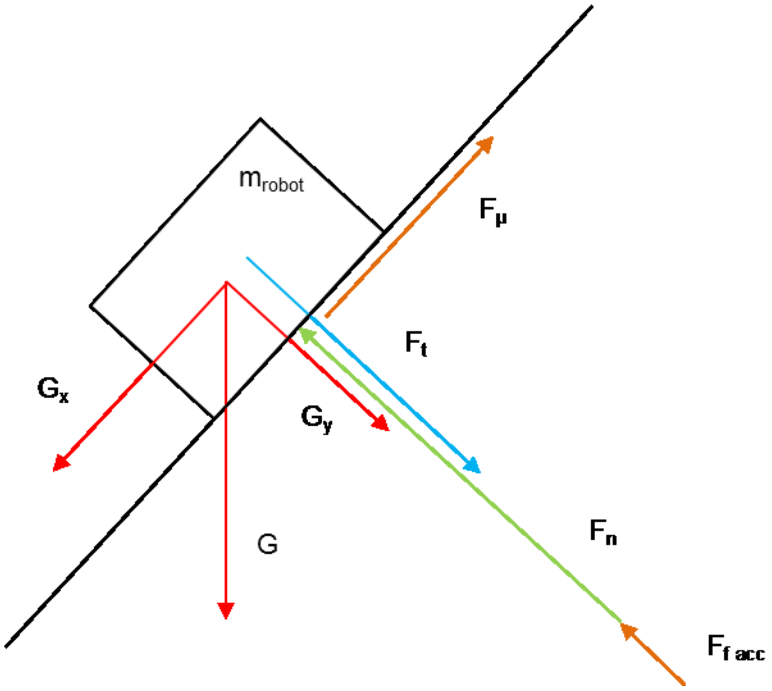

Figure 16. *Free body diagram of a robot with static thruster*

As also already explained in chapter 3, the force keeping the robot on surface is result of the thrust and friction generated by the thrust. The thrust required to generate sufficient friction to accelerate and to keep the robot on the surface can be deducted from the free body diagram seen in Figure 16:

$$\boldsymbol{F_t} = \frac{\boldsymbol{G_x - G_y \cdot \mu + F_{f\,acc}}}{\boldsymbol{\mu}}. \tag{13}$$

As can be noticed from the equation (13) the required thrust is dependent on G_x and G_y, which again depend on the inclination angle α according the equations (11) and (12).

For a robot with mass of 1kg, the required thrust could be plotted as a function of the inclination angle α as seen in Figure 17.

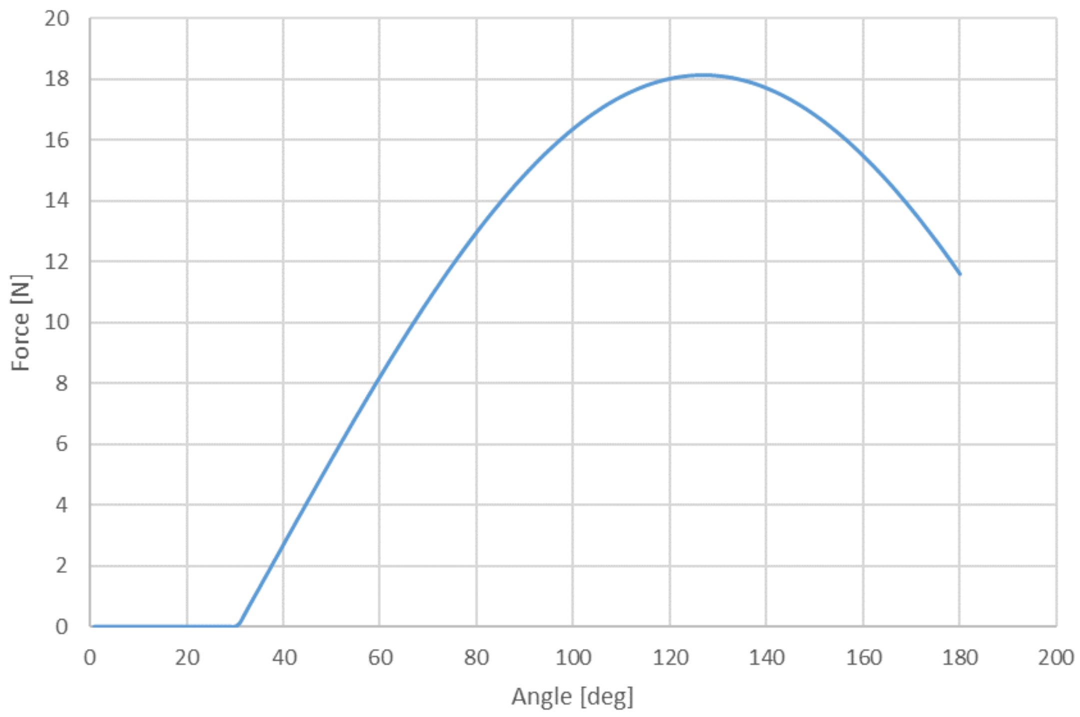

Figure 17. Static thrust required as a function of the inclination angle

The maximum required thrust can be defined by differentiating the equation (13). In the situation presented in Figure 17 the maximum thrust required would be 18.122 Newtons at 126.87 degrees inclination angle. This is the angle where the thrust has to work directly against G_y and generate friction to work against G_x, and the combination of these is at its highest.

If for example a propeller with 7 inch diameter and 4 inch pitch is used, the thrust generated according the equations (5) and (6) would be as seen in Figure 18.

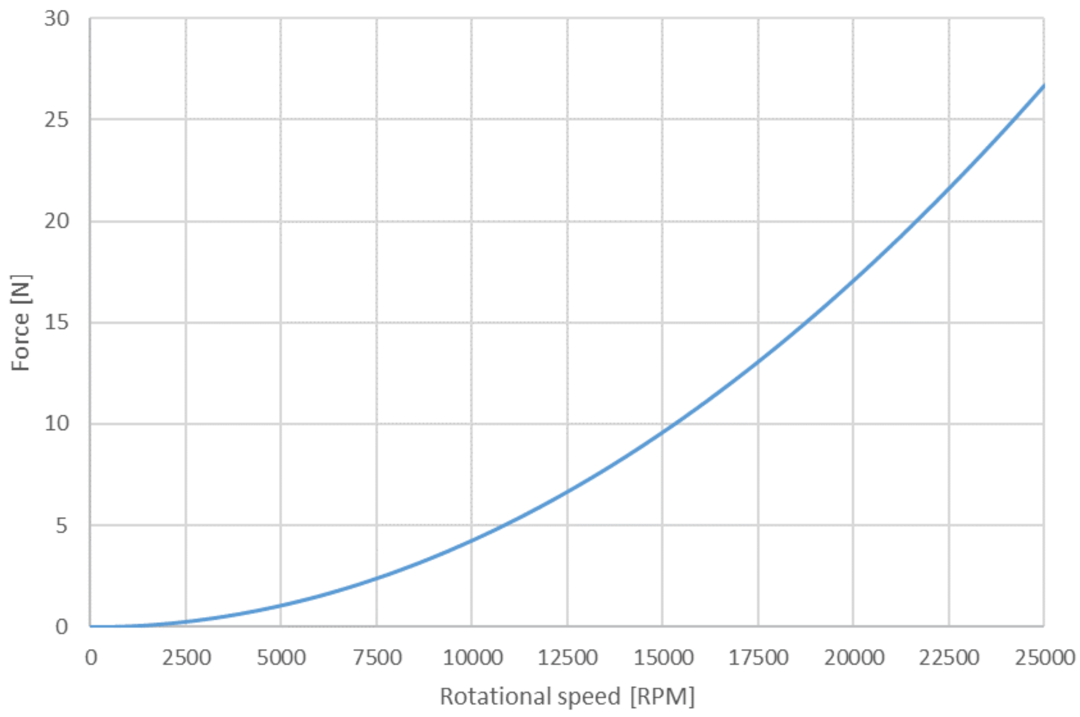

Figure 18. *Adhesion force as a function of propeller rotational speed*

Here the propeller should be able to spin over 20000 RPM in order to generate sufficient adhesion force for a robot weighing 1kg as seen in Figure 17. From above mentioned equations (5) and (6) can be deducted that a propeller with larger diameter or pitch would generate higher thrust force for same rotational speed.

5.1.2 Thrust vectoring

Calculating the required thrust with thrust vectoring is a bit more complicated than with static propeller. Instead of using raw power to keep the robot on wall, the thrust is channeled to a direction seen as most optimal. The principle is presented in free body diagram seen in Figure 19. However, this figure only presents one possible situation, and as the inclination angle of the surface would change the direction of thrust force F_t could change as well.

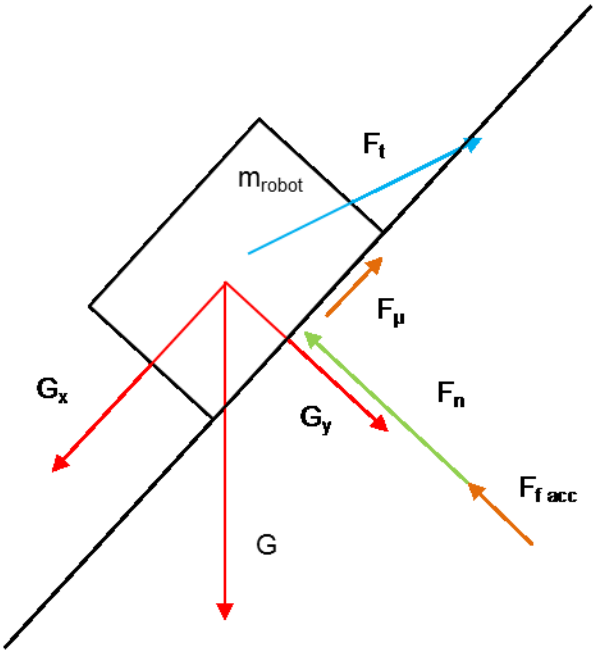

Figure 19. *Free body diagram of a robot with thrust vectoring*

As with the static propeller, there has to be always at least $F_{f\,acc}$, defined by equation (9), amount of force towards the surface in order to have friction that is not used to keep the robot on wall. Finding a single equation to present the minimum required thrust, like seen with the static propeller in equation (13), would be difficult, as the direction optimal thrust direction will change according the direction of gravitational force G components. Thus, the required thrust will be defined as a piecewise function.

Similar to static thruster case, between angles 0° to 30.625° no thrust is required. Most of the force from the mass of the robot is directing roughly towards the surface the robot is moving on, and therefore is able to generate sufficient friction. The exact angle where friction won't be sufficient to ensure traction required for acceleration can be calculated from the equation (10).

After inclination angle of 30.625° the G_y component of the robot's gravitational force is no longer enough to provide sufficient friction for acceleration and to counter the effects of the G_x. Thrust has to be added either to the opposite direction than the G_x or in same direction with G_y in order to increase the friction. The most efficient way would be to combine these both and direct the thrust slightly downwards from the robot horizontal line. However, this will cause problematic nonlinearities in thrust source tilt angle. Therefore, the more viable option is to direct the thrust against G_x. The thrust required from the propeller can be solved with equation

$$\boldsymbol{F_t} = .\boldsymbol{G_x} - (\boldsymbol{G_y} \cdot \boldsymbol{\mu} - \boldsymbol{F_{f\,acc}}) \tag{14}$$

The method described above is counting on G_y component of G providing the required friction between the robot and the surface. After certain angle the G_y component is no longer great enough to provide sufficient friction. This angle can be solved by solving the angle α from equation

$$G \cdot cos(\alpha) \cdot \mu - F_{f\,acc}. \tag{15}$$

The angle is approximately 79.556°. After this angle the thrust F has to be directed more towards the surface in order to increase the normal force creating the friction. Required thrust can be calculated with equation

$$F_t = \sqrt{(G_x)^2 + \left(F_{f\,acc} - G_y\right)^2}. \tag{16}$$

The thrust is generating opposite force for G_x and increasing the force towards the surface in order to ensure $F_{f\,acc}$ is satisfied. This equation is valid until the surface inclination α passes 90 degrees and G_y is no longer directed towards the surface but rather away from it.

As the inclination of the surface passes 90 degrees, the G_y will point away from the surface, and will not provide any support or friction. In fact, it will pull the robot away from the surface. Thus, the thrust has to do both generate enough friction to move and counter the effects of the gravity. The required thrust for surfaces with inclination angles larger than 90 degrees can be calculated with equation

$$F_t = \sqrt{\left(G \cdot sin(180° - \alpha)\right)^2 + \left(G \cdot cos(180° - \alpha) + F_{f\,acc}\right)^2}. \tag{17}$$

As all the parts of the piecewise function are known, the required adhesion force can be presented as:

$$F_t = \begin{cases} 0,\ x < 30.625° \\ G_x - (G_y \cdot \mu - F_{f\,acc}),\ 30.625° \leq x < 79.556° \\ \sqrt{(G_x)^2 \cdot + \left(F_{f\,acc} - G_y\right)^2}, 79.556° \leq\ x < 90° \\ \sqrt{\left(G \cdot sin(180° - \alpha)\right)^2 + \left(G \cdot cos(180° - \alpha) + F_{f\,acc}\right)^2},\ 90° \leq x \end{cases} . \tag{18}$$

Overall the thrust curve for a robot with mass of 1kg all inclination angles from 0 to 180 degrees will look like seen in Figure 20.

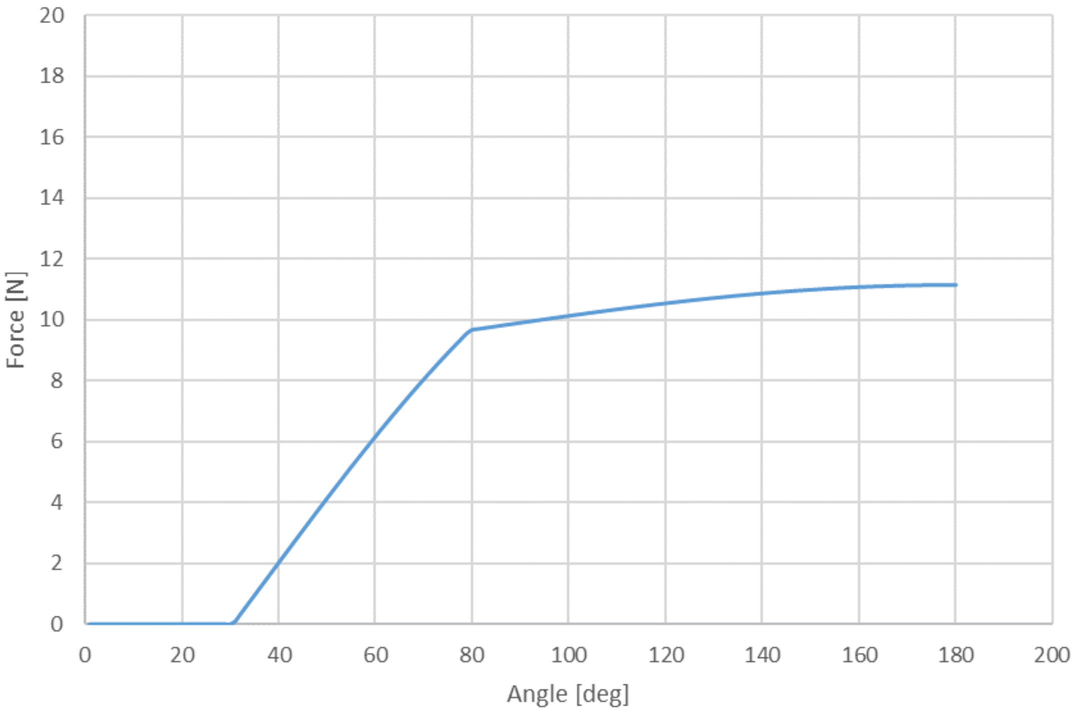

Figure 20. *Thrust required as a function of the inclination angle*

As the required thrust is known, the angle between the robot chassis and the propeller can be calculated for inclination angles over 79.556° with function

$$\boldsymbol{\beta = asin\left(\frac{G\cdot sin(\alpha)}{F_t}\right)}, \tag{19}$$

where the thrust F_t is depending on the angle α of the surface inclination. Before the angle of 79.556° the thrust will be directed against G_x and therefore the angle is 90 degrees. In Figure 21 can be seen that the angle of propeller varies between 0 to 90 degrees. This means the propeller requires rather great space reservation to move freely in every possible angle.

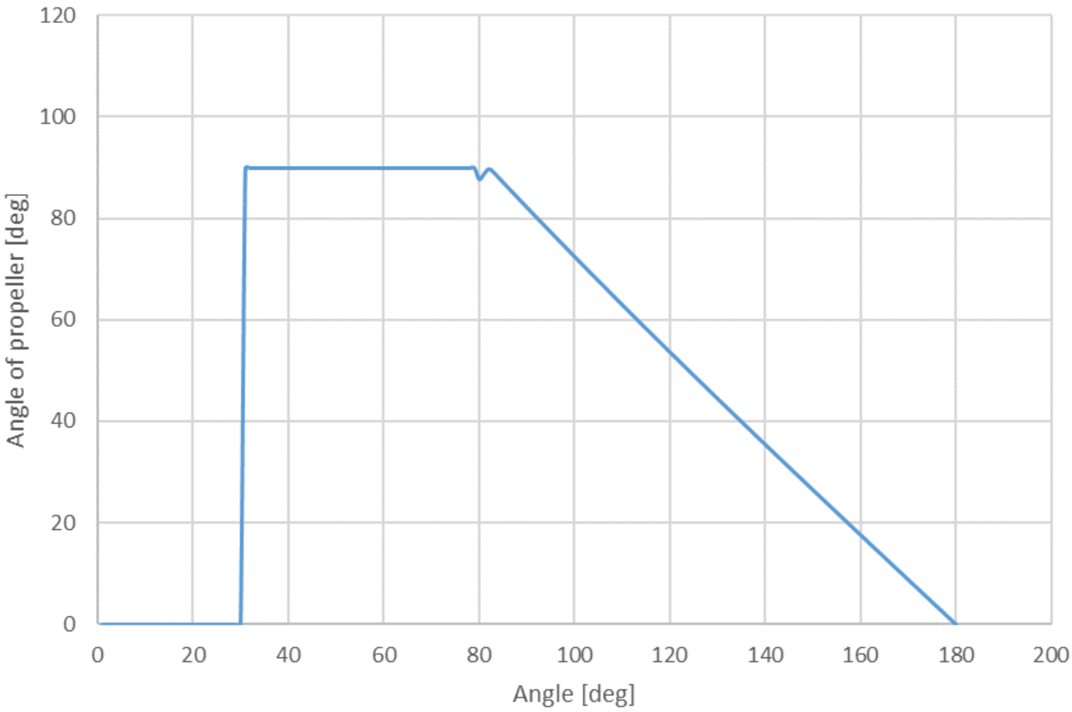

Figure 21. *Angle of the propeller as a function of the inclination angle*

These angles are in respect to the surface the robot is moving on. In practice, as the robot should be able to move on walls horizontally, vertically, diagonally and everything in between, the correct angle can't be reached with single degree of freedom. The propeller mounting system would require two degrees of freedom in order to be able to react to robot changing its direction. The structure should be similar to VertiGo robot seen in Figure 6.

Additional actuators and structural components will lead to higher weight, which again will lead to higher thrust requirement. If mass increase of 500g is assumed due to the more complicated structure and additional actuators, the required adhesion force would be as presented in Figure 22.

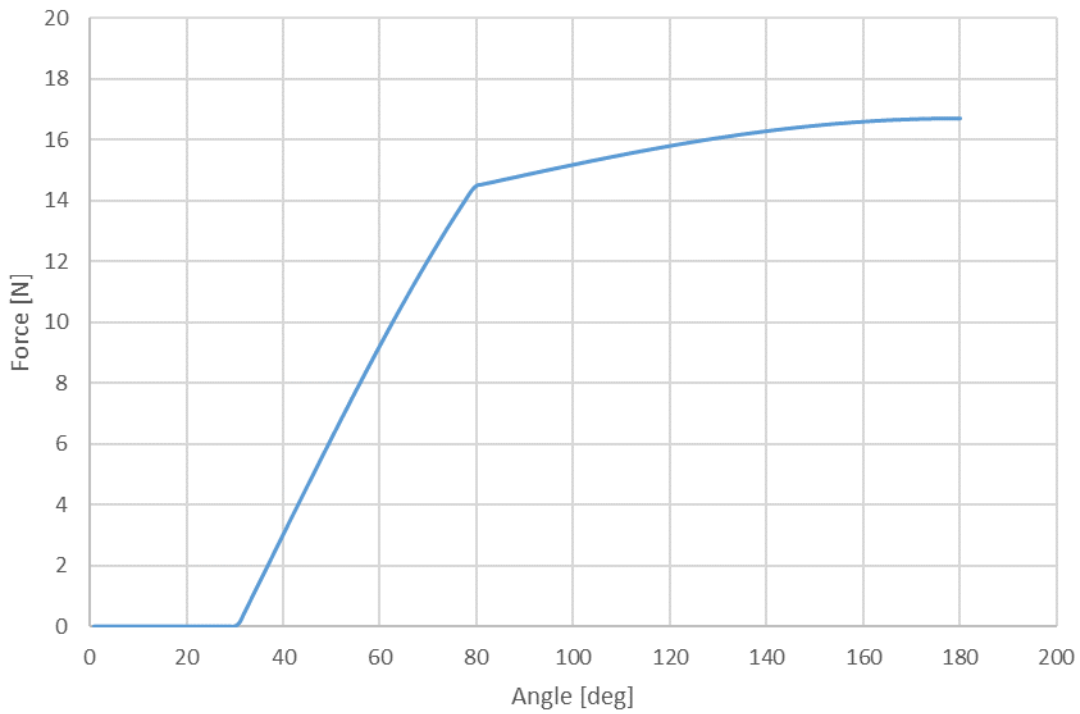

Figure 22. *Thrust required as a function of the inclination angle for robot with mass of 1.5kg*

From the Figure 22 can be seen that despite increased weight the maximum force required is lower than in case of lighter static propeller presented in Figure 17. The mass of the thrust vectoring concept can be increased by approximately 620g before the required force will be the same as with static thrust concept weighting 1kg.

As thrust vectoring is based on propeller thrust, the required rotational speed can be estimated from Figure 18 and compared to static thruster of similar size. Given the assumption of approximately 500g higher weight of the robot, approximately 19800RPM would be required from similar sized propeller to what was used in plotting Figure 18.

5.2 Static thrust with a duct

The required adhesion force does not change if propeller ducting is used or not, if the thrust direction is static towards the surface. However, propeller ducting has other positive characteristics. As explained in chapter 3.4 ducting might increase the efficiency of propeller decreasing the effects of the turbulence at propeller tips. With proper duct opening design the thrust can be also increased according to equations (2) and (3) due to higher air velocity around the opening.

Exact effects or propeller duct in midair are difficult to determine, but if the propeller is static in relation to robot chassis, the effects can be calculated more precisely as dimensions of a gap between the duct and surface are known. As the air velocity is in subsonic speeds, the air can be assumed as an incompressible fluid [12] and therefore the mass flow to be constant according to equation

$$\dot{m} = \boldsymbol{\rho \cdot v \cdot A}. \tag{20}$$

Thus, in situation like presented in Figure 12 the mass flow between the ducts lip and surface can be assumed to be equal to the mass flow through the duct and propeller. The mass flow rate can be estimated as the air density ρ can be either assumed to be relatively static or calculated if air pressure and temperature in surrounding air, and propeller area are known.

As the mass flow rate is known, the velocity of the air between the duct lip and surface can be calculated with the same equation (20) when the duct radius and gap between the duct lip and the surface is known. As the duct is round the gap area can be simply calculated with equation

$$\boldsymbol{A_{gap} = 2 \cdot \pi \cdot r \cdot h}, \tag{21}$$

where r is the radius and h the height of the gap.

The air velocity can be used to calculate the pressure difference between the gap and the atmospheric pressure in surrounding area, where the air velocity can be assumed to be 0 m/s, with equation (3). Due to the duct lip being round and the area being dependent on the radius, the pressure is also dependent on the radius and therefore not static everywhere under the lip. The pressure difference is smaller near the outer edge of the lip than near the inner edge close to the propeller.

Due to pressure and the area of duct lip both changing as a function of the lip radius, these can’t be simply multiplied as in equation (1). The force induced on the lip can be solved by forming a function between the pressure in every point on certain radius and the length of circle of a same radius. This function can be integrated in order to get the total force generated by the lip:

$$\boldsymbol{F_{duct} = \int_{r_{in}}^{r_{out}} p \cdot 2 \cdot \pi \cdot r}, \tag{22}$$

where r_{in} and r_{out} are the inner and outer radiuses of the duct lip and the pressure p is as a function of the gap height and duct lip radius as the velocity of air inducing the pressure according to equation (3) is determined by the gap area.

The total force keeping the robot on angled surfaces is the combination of the thrust from the propeller and the suction from the duct lip. In order to control and optimize the force both the thrust from the propeller and suction induced by the duct lip has to be presented as a function of propeller rotational speed or control signal.

Both can be seen as a function of air velocity, either through propeller or through the gap under the duct lip. The velocity again can be presented as a function of propeller rotational speed according to equation (6) assuming the minimum and maximum radiuses of the propeller duct lip and the duct height from the surface needed in equation (21) are known.

The total force can be simply presented as

$$\boldsymbol{F_{tot} = F_t + F_{duct}}. \tag{23}$$

As the propeller is not moving, the v_0 in equation (5) can be assumed as zero and the thrust induced by the propeller can be written as

$$\boldsymbol{F_t = \frac{1}{2} \cdot \rho \cdot A \cdot \left(s_{pitch} \cdot \omega\right)^2}. \tag{24}$$

Here the propeller dimensions, pitch and diameter and thus area, can be defined and are therefore known. The air density can be either measured or assumed to be static if the environment is known.

Also, most of the duct dimensions are known if propeller dimensions are known. The integral in equation (22) can be calculated, and the equation can be written in form

$$\boldsymbol{F_{duct} = \frac{\rho \cdot A^2 \cdot s_{pitch}^2 \cdot \omega^2}{4 \cdot \pi \cdot h^2} \cdot \left(ln(r_{out}) - ln(r_{in})\right)}. \tag{25}$$

The two equations, (24)***(25)*** and (25), combined will form an equation

$$\boldsymbol{F_{tot} = \rho \cdot A \cdot \left(s_{pitch} \cdot \omega\right)^2 \cdot \left(\frac{1}{2} + \frac{A}{4 \cdot \pi \cdot h^2} \cdot \left(ln(r_{out}) - ln(r_{in})\right)\right)}. \tag{26}$$

The total force as a function of propeller rotational speed can be seen in Figure 23. This is calculated using 7x4 propeller (diameter x pitch), 4cm ground clearance and 3cm lip around the propeller duct.

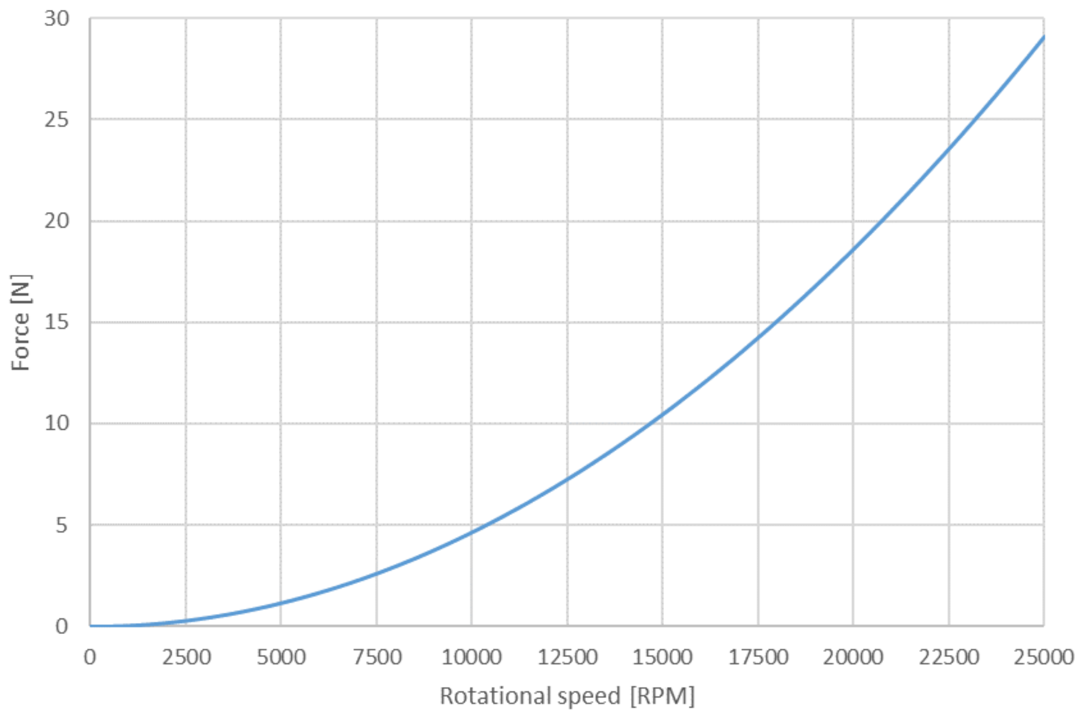

Figure 23. *Adhesion force of a ducted propeller as a function of propeller rotational speed*

As seen in Figure 23 the difference between ducted propeller and the thrust generated by a propeller without duct as seen in Figure 18 isn’t massive with these parameters. Yet as the duct properties can be adjusted also the adhesion force can be increased. For example, assuming other properties similar but halving the ground clearance a force of 10N could be achieved with about 9100RPM while with ground clearance of 4cm as seen in figure approximately 14700RPM is required.

Because the height of the gap between the duct and surface affects the suction force generated, adjusting the duct position could be used to increase the adhesion force on smoother surfaces or “lock” the robot in position if needed. A servo motor combined with appropriate linkage could be used to lower and raise the duct.

As the required adhesion force is similar to the static thrusting concept discussed in chapter 5.1.1, the ducted propeller should be more efficient due to slightly lower RPM requirement. When compared to the thrust vectoring option the maximum force needed is actually reached at similar propeller rotational speed.

As the required thrust is known to follow equation (13), it is possible to formulate an equation between the climb angle and propeller rotational speed. This equation is

$$\boldsymbol{\omega} = \pm \frac{\pi \cdot \sqrt{4 \cdot \pi \cdot h^2 \cdot (F_{f\,acc} \cdot \mu + G_x - G_y \cdot \mu)}}{\sqrt{\mu \cdot \rho \cdot (A^2 \cdot (ln(r_{in}) - ln(r_{out})) - 2 \cdot \pi \cdot h^2 \cdot A)} \cdot s_{pitch}}. \tag{27}$$

The negative values can be ignored as propeller speed can be only positive real number. The rotational speed can be seen as a function of the climb angle in Figure 24.

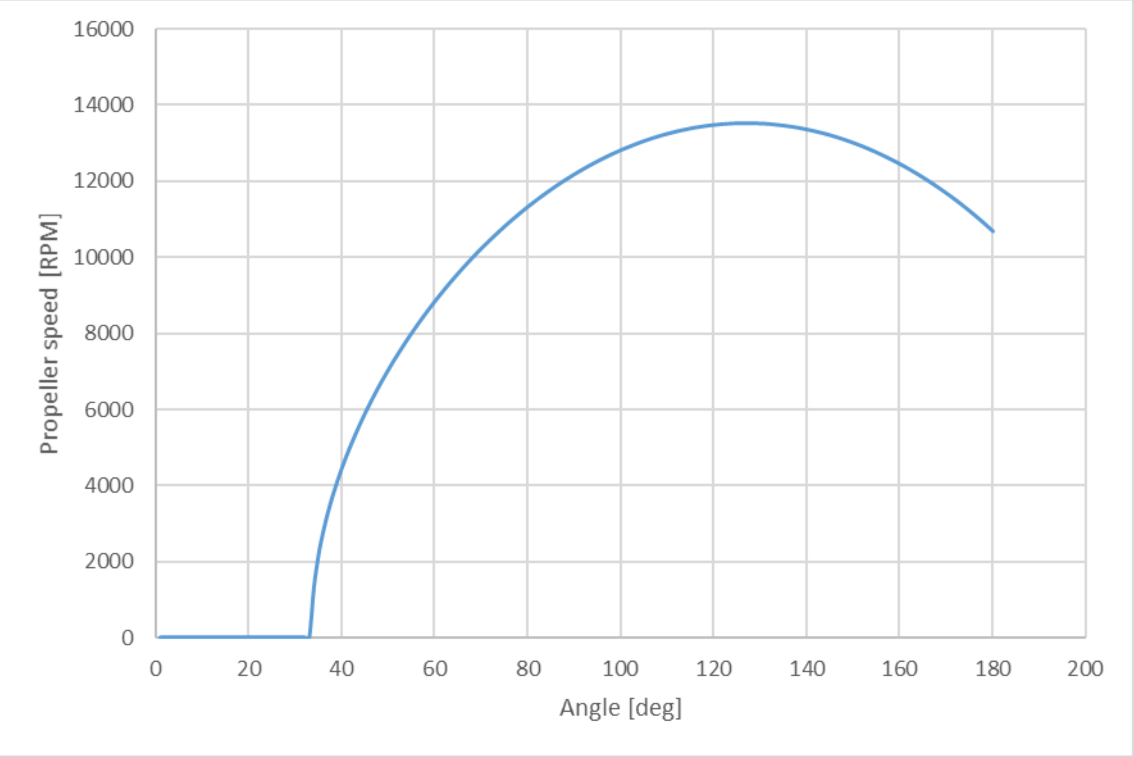

Figure 24. *Propeller rotational speed as function of angle*

The required propeller speed and the theory presented above does not take in account the possible benefits in propeller efficiency mentioned in chapter 3.4, as propeller efficiency is not taken in account in other concepts either. In practice there might be also some differences in duct efficiency depending on the actual design, as even small irregularities on duct surface might affect the airflow either positively or negatively.

6. COMPARING CONCEPTS

This chapter aims to compare the concepts presented in chapter 5 based on the list of requirements formed in chapter 4. There are multiple possibilities to compare different concepts in order to find the most suitable for further development.

Common decision-making tools include such as SWOT (Strength, Weakness, Opportunities and Threats) analysis, Pugh-matrix and decision making trees. Here for the comparison done in this thesis Pugh-matrix, developed by Stuart Pugh, is used. This is well known and handy method to compare things and concepts, especially in situations where available resources limit the possibilities to implement and test them in practice. Comparison leads to numerical result between the different options, which can be seen as more desired than for example mere verbal comparison. Requirements or features used as comparison criteria can be weighted according their importance, as all features may not be equally desired nor important. Weighting enables using uniform scale for comparison and desirability of a feature doesn’t have to be taken in account in grading different options.

Here concepts are compared on a scale from 1 to 5, where 1 represents the least good or desired option and 5 represents the best or most desired option. Different scale could be used as well. Some comparisons tend to use scale where the maximum amount of points is limited to for example 100 points. Here the maximum amount of points is not important as the point is to compare different options against each other, instead of some imaginary ultimate solution.

Rough sketches or the concepts being compared are presented in Figure 25. At top is a sketch of a robot with static propeller, in middle robot with propeller capable of turning and thrust vectoring, and the bottom represents a robot with propeller combined with duct and thus using both thrust and suction. Different colors represent placement of different components relevant to the comparison.

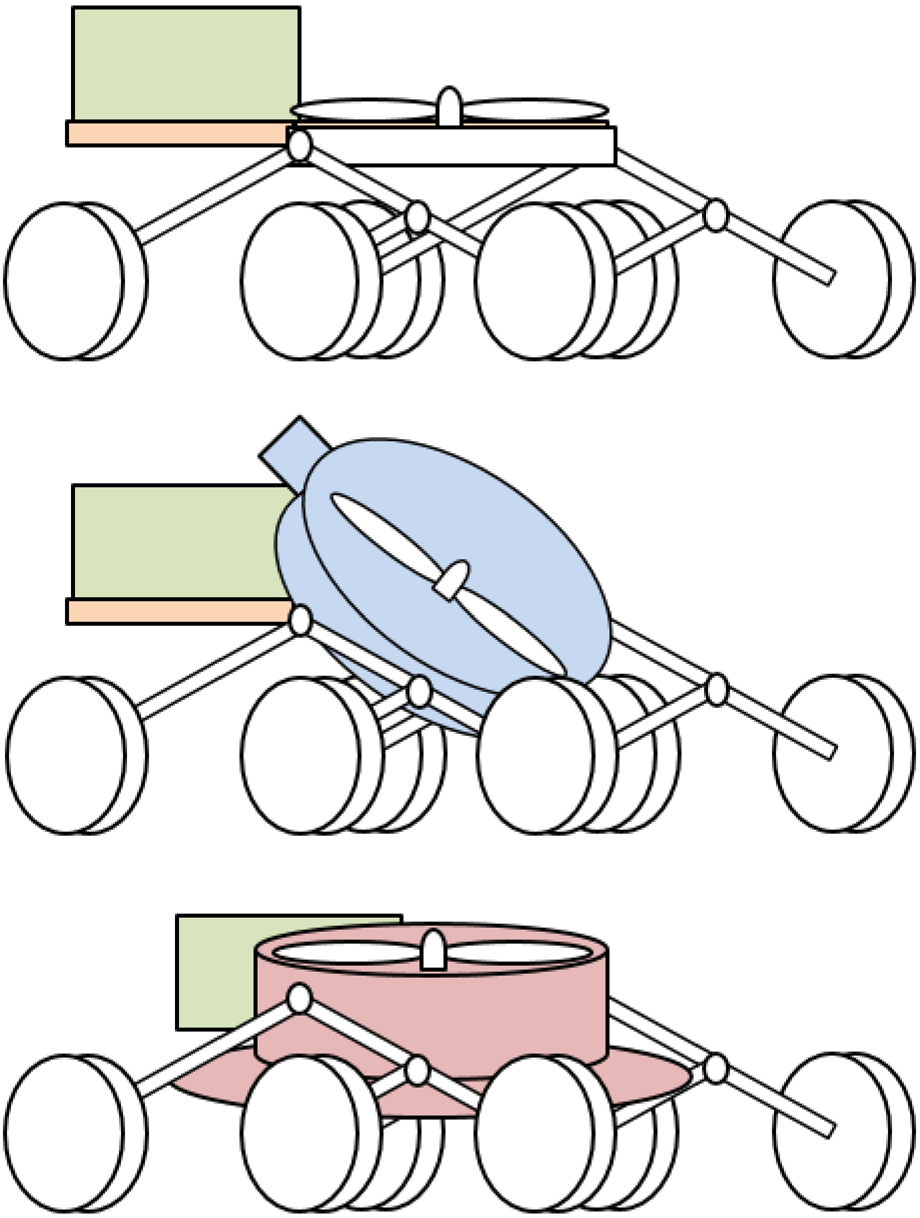

***Figure 25.** Rough sketches of the three concepts*

Without exact plans or even actual implemented prototypes of each concept the exact features and differences of these concepts may not be obvious. The main differences in their adhesion functionalities and theoretical performance was discussed in chapter 5 and the rough sketches may give an idea about how they might look like and what kind of features would be required.

The comparison is based both on theory formed in chapter 5 and knowledge and estimates done by the writer. Therefore, the end results shouldn't be seen as absolute truth, but rather as estimates done given the opportunities and limitations associated to the thesis work. Each of the requirements defined in chapter 4 were given an importance coefficient according to their relevance for the design process. The comparison matrix can be seen in Table 1 seen below.

Table 1. *Pugh decision making matrix*

Requirement	**Importance**	**Concept 1 Static thruster**	**Concept 2 Thrust vectoring**	**Concept 3 Static thruster with duct**
Required adhesion force	3	2	5	4
Weight	5	4	2	4
Ability to move on different surfaces	4	4	4	4
Ability to move omnidirectionally	4	4	4	4
Ground clearance	4	4	3	3
Form factor	2	4	1	4
Simplicity of structure	4	4	1	4
Simplicity of control	3	4	2	4
Total		110	81	112

From Table 1 can be interpret that the concept 3 would be the most suitable option for further development. The overall difference between the concepts aren't great as the difference between concepts seen as the best and the worst is only 26 points, which is 23% of the points given to the best solution.

Out of the concepts developed in chapter 5 the thrust vectoring is the most efficient way to achieve the adhesion based on the calculations. However due to inevitable weight increase, caused by the actuators and structures required to turn the thrust direction, the required rotational speed of the propeller would be rather similar to the concept 3 with ducted propeller, as stated in chapter 5.2.

Considering the weight of the robot a static propeller would be the most lightweight solution. Thrust vectoring requires additional actuators and structural elements, presented in Figure 25 with blue, in order to adjust the propeller direction with two degrees of freedom. Due to the space reservation needed for the propeller turning also other components such as the suspension require larger dimensions than what is needed with other options.

Ducted propeller would be slightly heavier than simple propeller without duct, but considering the material used and the fact that the duct can be designed to work as the robot's chassis the weight difference is minor. Simple propeller and concept with thrust vectoring would also need some structure to support e.g. the controller used and keep the wires away from propeller. These are represented with orange (additional structure) and green (controller) in Figure 25.

All of the solutions are based on rocker-bogie suspension and therefore the ability to move on different surfaces and omnidirectionally should be similar. The adhesion method might affect the traversing abilities by being able to provide higher adhesion force and therefore being able to conquer lower friction coefficient on some surfaces. This has not been taken in account due to lacking information about actual performance of the concepts.

The ground clearance is considered from point of view that it would be similar in all options. This may affect other properties of the concepts, such as required adhesion force or the form factor and it is considered while grading those properties. In theory static propeller should have the best adjustability while thrust vectoring requires large space reservation around the propeller and therefore ground clearance will affect the height of the robot. With ducted propeller the adhesion is partially based on certain ground clearance and therefore it shouldn't be allowed to alter too much in order to maintain sufficient adhesion force. These limitations in concepts 2 and 3 can be considered as negative effects, thus lower score was given.

Static propeller and ducted propeller are very similar considering the simplicity of the structure. Duct will require some additional material, represented with red in Figure 25, but as the structure can be used as chassis of the robot and to protect wires and other control system components from ending up in way of the propeller it can be seen very similar to the structure that would be required from static propeller as well. With more moving parts the structure of propeller capable of thrust vectoring is the most complicated. In order to implement the 2DOF moving ability of the propeller similar structure as seen in VertiGo presented in Figure 6 would be required. The rough sketch presented in Figure 25 is only presenting a single structure around the propeller, while there should be multiple to enable the propeller to turn in all directions. The space reservation also sets certain limitations to placing of the other components and affects the form factor of the robot. The static propeller and ducted propeller may have low form with the center of mass staying near the surface, but the option with thrust vectoring has the center of mass further away from the surface due to the space reservations needed for the propeller.

As with the simplicity of the structure the most effort to develop a working control system is required with the thrust vectoring option. It will require more actuators and possibly sensors if the built-in adjusting systems in actuators wouldn't work reliably. Static and ducted propeller are very similar considering the control system required for the adhesion force. Both systems are based on the rotational speed of the propeller which can be adjusted according the inclination angle and the main difference is the strength of control signal i.e. the rotational speed of the propeller.

7. IMPLEMENTATION OF THE WALL-CLIMBING ROBOT PROTOTYPE

The most suitable concept presented in chapter 5 was implemented in order to research the performance of the design in practice in addition to theoretical inspection. This makes it possible to gain information about whether the robot and theory behind it works as expected.

As the state-of-the-art review didn't reveal that rocker bogie suspension would have been ever used in a wall-climbing robot before, testing a prototype will also gain some information about how the suspension will perform. Due to high center of gravity some problems were to be expected, but the actual magnitude was unknown before the tests.

7.1 Robot design and structure

The components for the concept chosen in chapter 6 were chosen according the theory seen in chapter 5 and the robot chassis was designed around these in CAD (Computer Aided Design) software. The base of the structure is rocker-bogie suspension combined with the devices required for the adhesion method, which is in this case a propeller with duct around it.

As the design uses a duct to induce some suction certain design limitations, such as the ground clearance, had to be taken in account. Otherwise the structure design is rather free, yet it has to be light and strong. The robot structure is presented with an image of 3D model from CAD software in Figure 26.

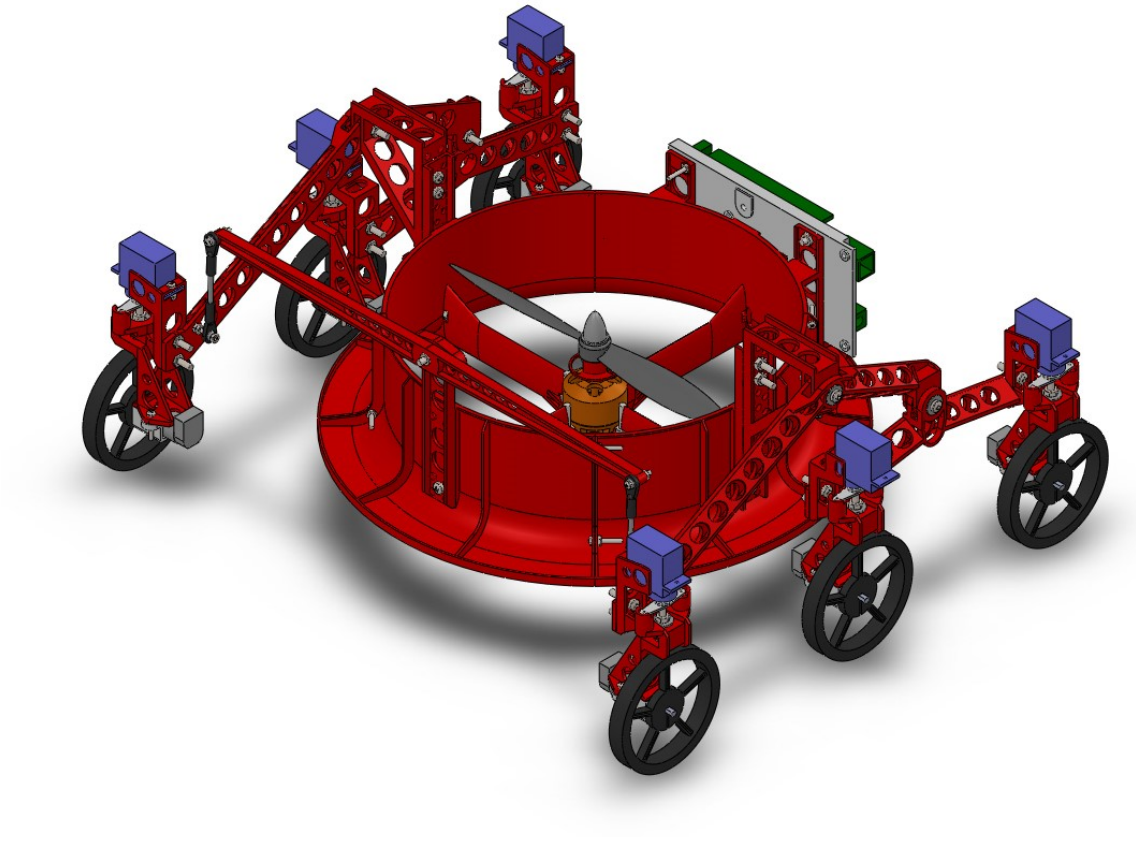

Figure 26. 3D model of robot design

The red parts see in Figure 26 are custom parts designed for the robot. These were 3D-printed with red PLA material. PLA is light, with density of approximately 1.2 to 1.4 g/cm^3 depending on the source, and it should be less prone to heat shrinking than for example other common 3D-printing material ABS plastic. The material was chosen due to suitable properties and good availability.

The measurements of rocker and bogie were chosen in a way the wheels would have equal spacing and they would also be the first components at each end to touch a possible obstacle. The height was mainly dictated by the steering components, bogie trajectory and the design chosen to avoid unnecessary stresses in the structure, i.e. torque in suspension joints. Multiple different rocker-bogie resigns have been suggested in scientific literature and elsewhere, but as this thesis mainly focuses on the implementation of the adhesion method fine-tuning the geometry of the suspension was not considered important.

Each wheel has its own drive motor and servo motor for steering. Drive motors are placed on same axis as the wheel due to compatibility and simplicity reasons, even though 90 degree gearing between the wheel and drive motor could have minimized the space requirement. The blue steering servos are placed above the wheels in order to optimize the pivot point. Steering isn’t needed for all of the wheels in rocker bogie suspension, but here it was added to the middle wheels as well in order to improve the traversing abilities of the robot. Slight increase in weight will affect the required adhesion force, but it was considered minor.

Due to the wheeled locomotion the robot is capable of speeds up to approximately 0.4-0.5 m/s on flat surface. The speed is electronically limited in order to keep the maximum average voltage on drive motors near the nominal voltage of 6V defined for the motors. This is done in order to conserve the motors and avoid unnecessary stresses on robot structure. Feeding motors voltages over the nominal voltage defined may shorten the lifespan of a motor and running into obstacles in high speeds might cause unwanted forces to the suspension components. Especially the steering servos may get damaged if there are unaccounted high lateral forces towards the wheels or other steering components.

As all of the six wheels are steered, it was possible to implement several different steering modes for the robot. These modes are presented in Figure 27.

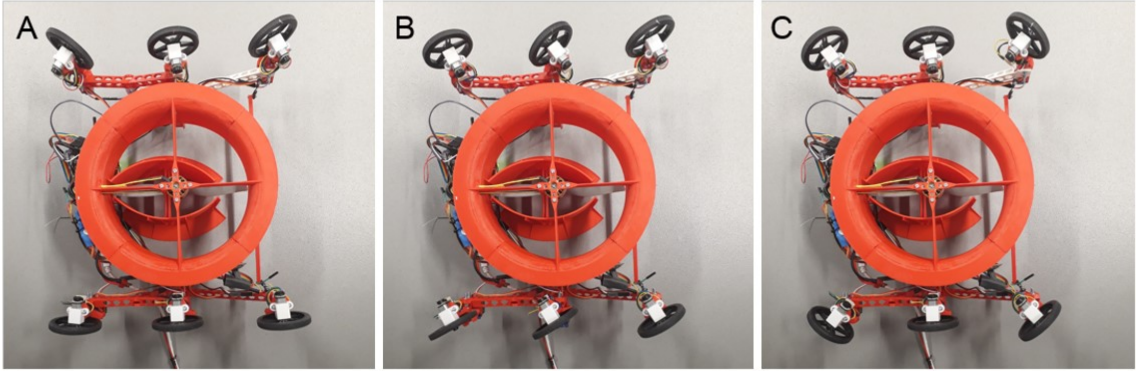

Figure 27. *Different steering modes implemented, normal steering (A), crab steering (B) and rotate steering (C)*

With normal steering (A) both front and back wheels steer according the Ackermann geometry. Crab steering (B) turns all of the wheels in same direction and the robot is able to move diagonally or even sideways. In the last steering mode, the robot is also able to rotate (C) around its own center point. With multiple steering modes the robot is rather agile and has a great ability to move evading obstacles.

However especially the normal steering mode could be developed further. Due to different wheel paths the outer wheels travel longer distance when the robot is turning and therefore require higher speed. The robot is slowing down the wheels on the inner side of the curve, while the outer wheels continue on speed determined by the user control. On tight turns this will lead to jerky behavior as inner wheels may decelerate almost to a complete halt. The speeds could be optimized e.g. by keeping the average speed as the user determined by decelerating the inner wheels, but also accelerating the outer wheels.

The middle of the structure includes a propeller, which is run with the orange brushless motor below it. The propeller duct was designed to act as structural element between the suspension components and to carry all of the electrical components like the main control board, voltage regulators and motor controllers. Major electrical components can be attached to the duct and wiring can be run safely avoiding the propeller blades. The light gray and green component at the other end of the robot is representing the main control board, which in this case was chosen to be Arduino Mega Rev3.

In actual robot there are multiple components that aren't visible in the image of 3D model, such as wires and motor controllers. These weren't modelled as their placement was rather free or they didn't require solid attachment points for screws. The actual robot built as part of the experiment can be seen in Figure 28.

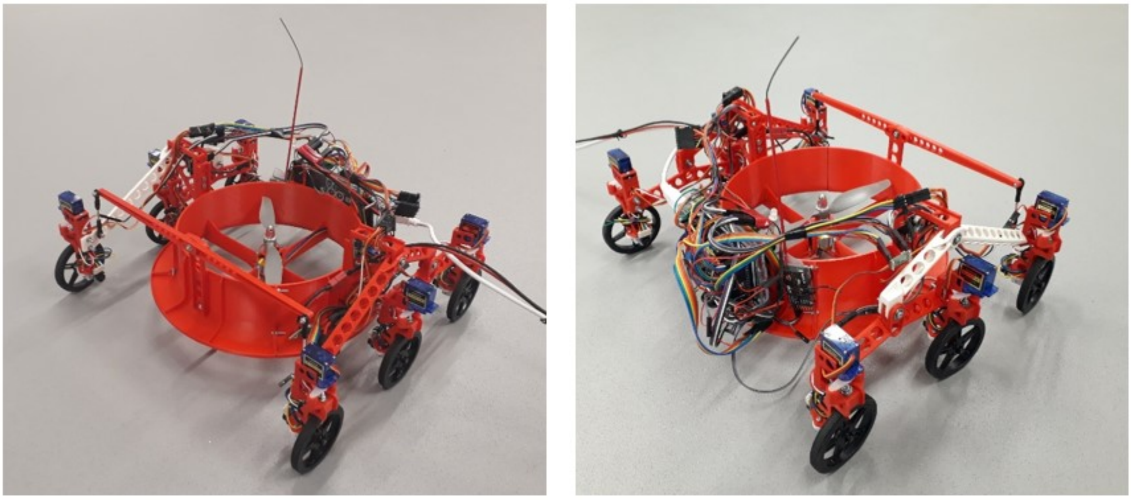

Figure 28. *Robot prototype*

The robot has modular structure in order to simplify the manufacturing process, but mainly to make development and prototyping process easier. A lot attention was paid to make the parts relatively easily replaceable and changeable, which proved to be worth the time during the testing phase as certain components proved to be too flexible or fragile.

It is difficult to calculate exact weight of the robot during the design phase as there is no information available of all parts, and for some parts the information may be incorrect. The actual prototype robot used for testing weights approximately 840 to 860g, of which some of the weight comes from the electricity and data cables attached to the robot. According to the theory presented in chapter 5 the required propeller speed would be as presented in Figure 29.

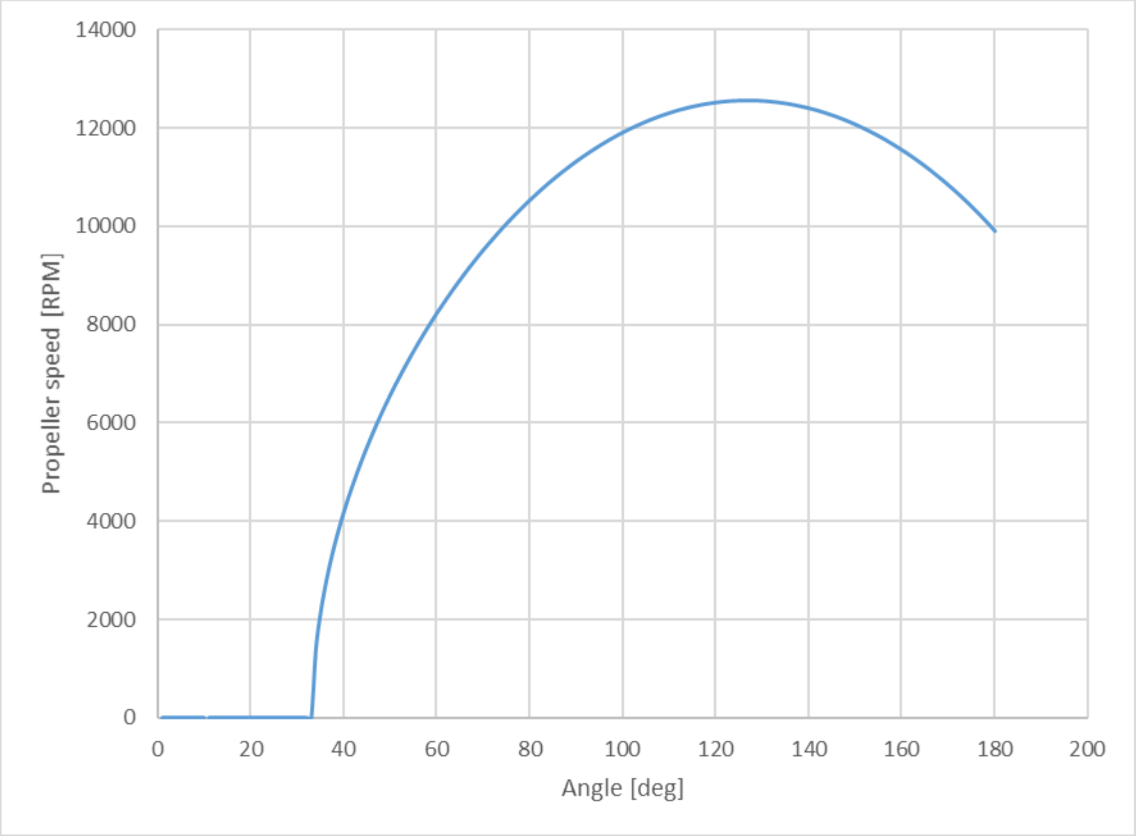

Figure 29. *Propeller rotational speed as function of angle*

Due to the weight being slightly less than what had been estimated in chapter 5 also the required propeller speed is lower. However, the difference is only approximately 1000RPM.

7.2 Controller

Controller chosen for the robot is Arduino Mega 2560 Rev 3. The controller has 54 digital I/O ports and 16 analog input pins. 15 of the digital I/O pins can also supply pulse width modulated (PWM) signal. Some of the digital pins can be also used for other special purposes, such as serials and interrupts. The board is based on Atmel ATmega2560 microcontroller with 16MHz clock speed. [3]

The Arduino Mega was chosen due to accessibility and large amount of available resources and references. The board itself is reasonably sized and equipped with suitable connections. Different Arduino boards are popular among robot enthusiasts and therefore an easy product to approach. The computational power may be limited, but it was discovered to be sufficient for the purpose.

The board has logic voltage of 5 volts and outputs for 5 and 3.3 volts. These outputs have low current capability, 50mA for 3.3-volt output, 20mA for I/O pins [3] while 5 volt output current is depending on the voltage regulator heat dissipation hence the board input voltage and current capability. In practice while Arduino may be capable of controlling all the devices in robot either with PWM or I/O signal, it will not be able to supply the power for them.

PWM signal is required to control all of the motors in robot and the steering servos. The drive motors also require I/O pins to determine the direction of rotation. Some of the sensors output analog signal, while some use special communication busses. Despite the great amount of different ports on the board, Mega wouldn’t be sufficient for much more complicated project. As most of the actuators used require PWM signal as input, and some of the suitable ports also have other features, this easily becomes a bottle neck.

The board uses Arduino IDE for programming and compiling the code. The language used is combination of C and C++, with some built in libraries for controlling the different interfaces on the board. The board firmware has two built in functions, setup and loop, which are automatically run when the board is powered. According to their names, setup is only run once and meant to e.g. define certain pins and variables, while loop is run repeatedly till the board is either reset or unplugged from power source.

For the prototype a simple logic structure could be made, where the loop is calling code functions responsible for different functions of the robot. The code structure used with the prototype is presented with simplified block diagram in Figure 30 below.

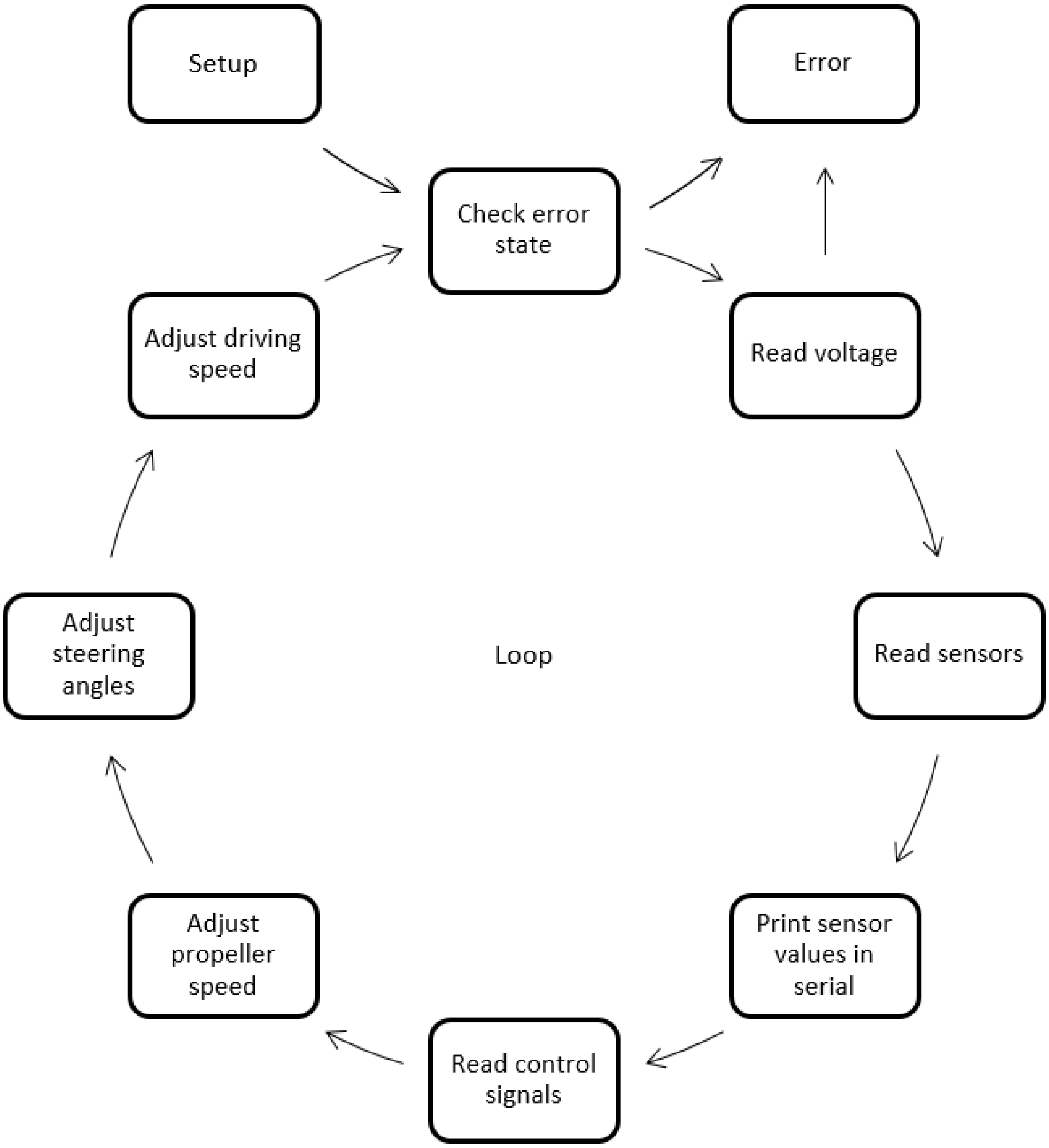

Figure 30. *Robots control structure*

As the program enters the loop it will first check possible critical errors that happened either during the setup, e.g. failure to initialize sensors, or during the last run of the loop. If no errors were detected the battery voltage is read and compared to preset values indicating the battery status. The status is informed to the user with an RGB led-light (Red, Green, Blue light emitting diode), unless the battery voltage is under the minimum limit, which might be harmful [14] for the lithium polymer (LiPo) battery used. Both detected error or too low voltage will prevent rest of the code from executing.

If an error state is not entered, the rest of the code can be executed. Robots sensors are read, and selected data sent to a serial port. For example, the exact value of the battery voltage can be read from the serial with a computer connected to the Arduino instead of relying on the led-light indicating preset voltage levels.

For testing the prototype, a radio controller was used, but also other solutions would be feasible. The control signals can be read and used to adjust different actuators. Propeller can be adjusted either by the manual control signal from controller or automatically according the robot orientation read from sensors.

7.3 Teleoperation

Radio control teleoperation was chosen as an initial control method for the robot, as it can be easily used to test the systems and operation without need to develop additional auxiliary systems. If the robot would be developed further, the teleoperation could be changed to more sophisticated system including control system running on separate PC.

Used controller system is Radiolink T8FB RC controller with R8EF receiver on the robot that has 8 channels. For the control there are two two-axis joysticks, two levers and two switches on the controller. The controller and receiver combination can be used either with 8 individual PWM outputs, a single S.BUS or PPM (Pulse Position Modulation) output. Of these the PPM output was chosen due to the possibility of transmitting all 8 channels in one signal. This requires less inputs from Arduino board and enables the possibility to use interrupt pins to receive real time data from controller all the time. The downside of using PPM is the fact that the single signal has to be read and modified to separate channel signals programmatically.

The signal consists of pulses of fixed length but variable time between the signals, which can be interpret as analog signal [6]. The information is encoded in the pauses between the pulses as presented in Figure 31.

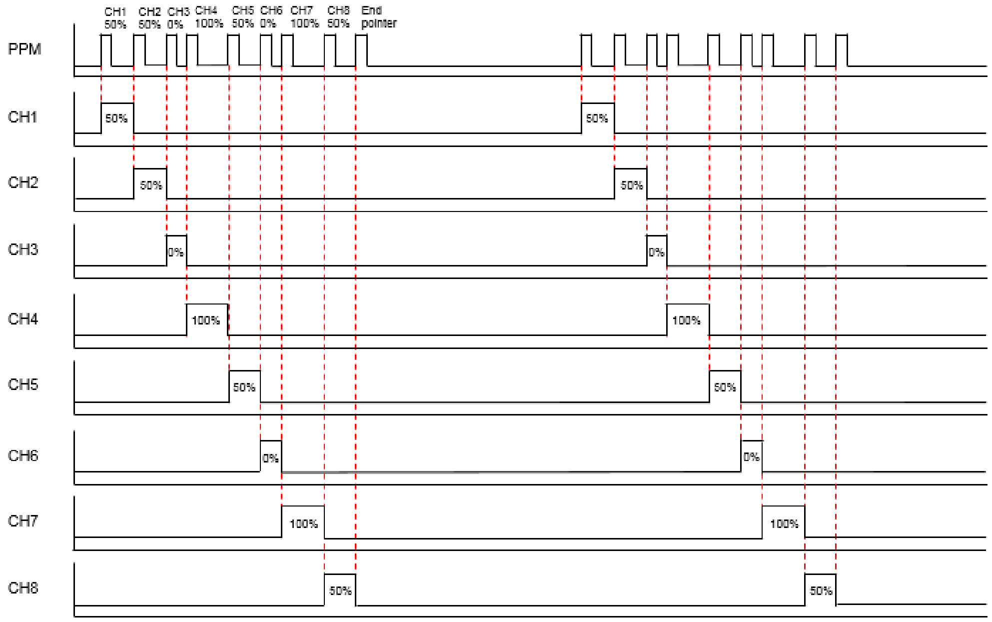

Figure 31. *PPM signal pulses*

Value of single channel can be defined by measuring the time between consecutive signal pulses. If a pulse has length of 500ms, the gap between pulses may vary from 500 to 1500 milliseconds, therefore adding up to total value of 1000 to 2000 milliseconds, which is commonly used as PWM signal range in RC components. There is also separate signal to signify the end of one group of channel values, as no other synchronization method is provided [6]. Therefore, with an 8-channel system a PPM signal consists of groups of 9 pulses with 5000 to 20000 milliseconds gap between groups.

The signal wire can be connected to Arduino interrupt pin. Interrupt pin detects every signal without need of actively polling the pin in Arduino code. Time between either falling or rising signals can be logged, and length of gaps calculated, which again can be interpret as PWM signals. By finding the longest gap between pulses, the signals can be assigned to correct channels. In practice the controller channel signals acquired with method explained above may vary even if the input should be static. This is most likely due to poor quality of parts and no built-in noise filters. For example, a simple solution of moving average of five consecutive values can be used to level the control signals on each channel.

As the development work done focuses on the robot movement, there was no need for all channels. Basic robot movement can be done with less than 8 channels and if additional functionalities would be required, these could be implemented with simple switch functionality between drive and work modes. This could almost double or triple the functional channel amount as one of the channels would be always used as a switch while the rest could change their functionality according the switch position.

7.4 Adhesion system implementation

For the prototype made for testing the thrust source chosen for the robot was an APC 7x4E propeller with 7-inch (177.8 mm) diameter and 4-inch (101.6 mm) pitch, rotated by Suppo A2208/14 a brushless electric motor. The combination was chosen iteratively according the required propeller speed calculations seen in chapter 5 while trying to keep the propeller size, and therefore the robot’s size, relatively small.

According to equations seen in chapter 5 this size of propeller should be satisfactory for robot weighting 860g if approximately 12600RPM can be reached. It would be reasonable to define the propeller and motor combination in a way there would be additional thrust generated all the time or thrust could be increased significantly if needed. This way the robot wouldn’t be as sensitive to possible problems, such as leakages under the duct or small differences in efficiencies that hasn’t been taken in account in calculations. In order to increase the maximum thrust either propeller diameter, pitch or rotational speed should be larger. However, as motors suitable for larger propellers are often rated for lower rotational speeds and motors with higher rotational speeds are rated for smaller propellers a compromise was made in order to gain information about actual performance compared to values given by the manufacturer.

There are also certain limitations choosing the propeller. Propeller manufacturer has suggested maximum rotational speed for the propeller [2]. This can be calculated with equation

$$\boldsymbol{RPM_{max}} = \frac{\mathbf{145000}}{\boldsymbol{d_{prop}}}, \tag{28}$$

where propeller diameter d_{prop} should be in inches. For a propeller with 7inch diameter the maximum allowed rotational speed would be 20714RPM according the equation. Some sources state the propeller tip shouldn't exceed the speed of sound [12] and with the equation presented above the tip speed should stay well under this.

The motor and propeller should match in order not to demand more current from the motor than it can handle. The motor manufacturer recommends using similarly sized propeller for the motor in question. The manufacturer is stating [26] that 14 pole motors like A2208/14 might be able to reach up to 20000 RPM when attached to their ESC. The manufacturer is also reporting theoretical KV value of 1450 [25] for the motor, which is often interpret as RPM to voltage ratio. This would give maximum rotational speed of 18270 with 12,6V battery voltage, which should be also suitable according the equation (27), of which results can be seen in Figure 24. However, some sources [21] state the maximum RPM would be related to electrical frequency of the ESC instead of KV value in brushless motors, as the changes in motors magnetic field are controlled with ESC instead of commutator inside the motor, like in brushed motors. According the calculations seen in chapter 5.2 these rotational speeds should be enough for all situations for a robot weighting approximately 1kg, which is slightly more than the actual weight measured from the prototype.

In practice up to 20000-22000 RPM was measured with full battery without any load on motor, and as the battery charge decreased the motor was capable of reaching only approximately 16000 RPM without load. With propeller attached the motor is capable of reaching approximately 12000RPM at best. This indicates the robot will not be able to operate on all inclination angles, but the adhesion and actual maximum inclination angle can be tested. There is a clear difference in theoretical maximum speed of the motor and the actual maximum speed of the motor under a load.

Robot has a duct with 3cm wide lip around the bottom. The lip is on height of 4cm from the surface. According the theory seen in chapter 5.2 the duct should be able to induce suction force of approximately 5N at propeller speed of 10000 RPM and approximately 11N at 15000 RPM. In practice due to 3D-printing the duct in multiple pieces the shape may not be the most efficient and further experiments would be required to define exact effects of the propeller ducting and its shape in practice.

The robot has six rubber wheels. Due to the rocker bogie suspension system, these should be almost all the time in contact with the surface the robot is driving on and therefore being able to produce some friction. The friction coefficient measured for the wheels is approximately 0.75, but due to different surface properties this may vary. The friction coefficient was found by testing the maximum tilt angle of a surface before the robot starts to slide.

7.4.1 Acceleration sensor

In order to automatically adjust the adhesion force generated by the propeller, the climb angle has to be known. Waveshare 10DOF sensor was chosen for the purpose.

The sensor has 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, and sensors for temperature, pressure, and altitude on same board. Data from sensors is sent through I^2C bus, so the data from multiple sensors can be handled with relatively small amount of wires. [32]

Using accelerometer is a simple way to define the climb angle. The accelerometer measures the acceleration in x, y and z directions and due to gravity, there is always acceleration in some of these directions. When the robot is static, there will be 1g of acceleration towards the ground. By placing the sensor in a way that one of the three axis is pointing towards the surface the robot is moving on, on a horizontal surface the sensor should output 1g on that axis assuming the surface and robot are static. When the robot starts to tilt in any direction the acceleration due to gravity starts to shift to other axis of the sensor and the result measured from the axis pointing the surface starts to decrease. By taking an arcus cosine of this result, the tilt angle can be measured, but the actual tilt direction is not known. With a ducted propeller solution where the adhesion force is always directed towards the surface, only the tilt angle value is required.

However, the accelerometer also measures the accelerations caused by movement of the robot. The movement appears mainly as irregular spikes in the measurement data, and these can be filtered by simply taking a moving average of the value. Moving average is slow to react on changes and not entirely accurate if the robot is moving a lot. However, as the robot’s movements should be relatively slow, slight errors in measurements shouldn’t be a problem considering the fact the robot is just a prototype. Furthermore, if the required adhesion level would be defined above the minimum value, slow reaction to inclination angle changes or small variation in produced adhesion force would be acceptable.

7.4.2 Propeller speed adjusting

Propeller speed required to induce sufficient force can be calculated with equation (27) seen in chapter 5.2. However, this equation is purely theoretical and doesn't take in account possible losses in system. Therefore, the prototype is built to be used to test the equation in practice.

The equation (27) can be simplified as the dimensions of the robot, such as propeller diameter and pitch, duct lip radius and ground clearance, are known. This will reduce the computational load from the robot controller as the amount of required calculation operations is reduced. Considering the low computational frequency of the Arduino mentioned in chapter 7.2, this will benefit the system as the controller board will be capable of calculating the desired value for propeller speed, steering and drive speed more frequently.

In their tests Zulkipli et al. [34] found the propeller RPM to have almost linear response to throttle percentage which is in practice the ESC input PWM signal. Assuming these results could be generalized for different components, simple open loop control would be possible and there would be no need to measure the propeller speed. However, the tests done by Zulkipli et al. were done under free load, and therefore may not fully apply to conditions where the motor is loaded. Therefore in order to adjust the speed of the propeller according the equation (29)(27) the actual propeller speed has to be known. The motor speed is adjusted with a PWM signal going to ESC, which will define the frequency of the voltage pulses going to motor.

As mentioned earlier in chapter 7.4 the connection between the motor KV value and actual rotational speed may not be as clear as with brushed DC motors and can be relied even less if motor has load. There are 3 wires going from ESC to brushless motor, each varying voltage between zero and maximum value. In theory if average voltage from one wire would be measured, it might have connection to the motors rotational speed. However, as the voltage is variable, all sensors may not be able to measure it reliably. Even if the voltage could be measured, the actual relation between the rotational speed and voltage should be verified and ensured using for example optical sensor to measure the rotational speed. In addition, the PWM signal controlling the ESC should be considered, as the relation between the PWM control signal and ESC output is unknown. Due to complexity and unreliability explained above measuring the rotational speed of a brushless motor from motor input voltage is not used in the prototype. Instead the rotational speed is measured with analogic optical sensor. The sensor is an incremental encoder outputting pulse signal depending on light level. In order to use it as a rotary encoder a rotating disk with one or more slits is required on motor output shaft. For this purpose, a custom disk with two slits was 3D-printed as seen in Figure 32 presenting the structure.

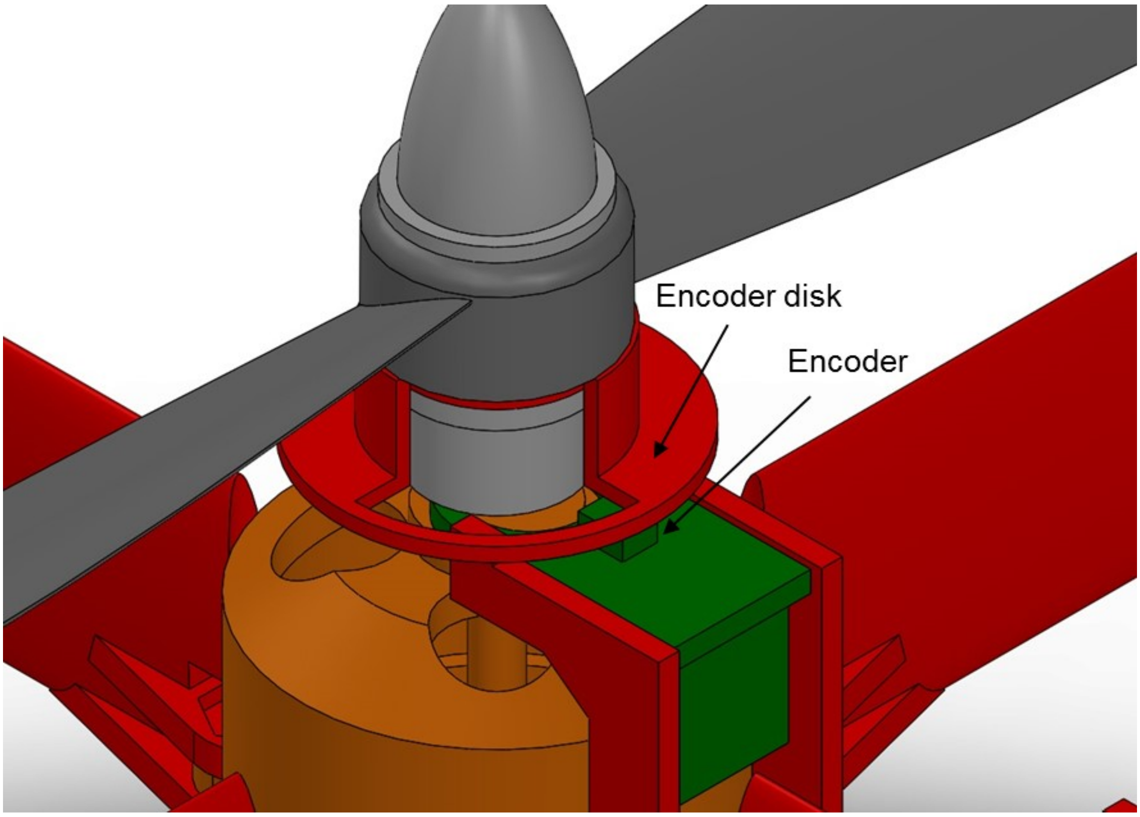

Figure 32. *3D model of propeller motor encoder setup*

As presented in figure the encoder disc is connected to the propeller hub and it has two slits on opposite sides. Green piece is presenting the encoder device, which has to be as close to the encoder disc as possible in order to reliably detect the changes in light level. Because the optical encoder is used, it won't work in dark environments unless an additional light source would be added.

The signal from optical encoder is connected to interrupt pin on Arduino to ensure registration of each signal. As the sensor output signal is analog, the strength is relative to input voltage and light level detected by the sensor. The Arduino interrupt pin is digital and detecting changes between high and low states. These are defined in documentation [4] relatively as above 3V and below 1.5V. In order to reach low enough signal values, the sensor input voltage has been connected to 3.3V pin.

In practice the sensor is measuring the number of revolutions since powering up the robot. As the code on Arduino boards is run in constant loop, the rotational speed can be calculated by comparing consecutive loop executions and dividing the difference in revolutions by the difference in time acquired from Arduino millisecond clock. The equation would look like:

$$\boldsymbol{\omega} = \frac{\frac{\boldsymbol{i_n - i_{n-1}}}{\boldsymbol{2}}}{\boldsymbol{t_n - t_{n-1}}}, \tag{29}$$

where i is the number of rotations, t the time acquired from Arduino clock and n the ordinal of the loop executed. As the encoder disc has two slits, every revolution is registered twice, therefore the sum of revolutions has to be divided by two.

The required propeller speed can be calculated with equation (27) and compared to the actual rotational speed measured with the optical sensor. However, as the ESC is controlled with PWM signal between 1000 and 2000ms, the difference in required and measured propeller speed has to be converted to PWM signal. In practice the control system is similar to P-control, but the control signal is saturated to minimum and maximum values. These values are added to previous PWM control signal. The idea is presented with a block diagram in Figure 33 below.

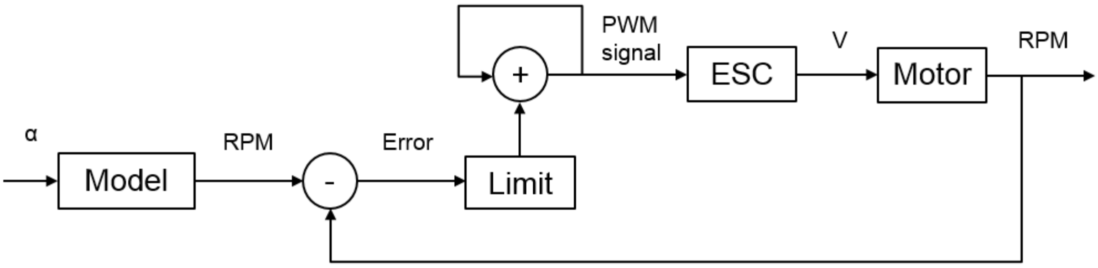

Figure 33. *Control logic*

By saturating and adding the error signal to the PWM signal systems reaction time can be adjusted. In this case the ESC and motor react quickly to variations in control signal and therefore the error signal is strictly limited to slow down the reaction. Without slowing down the reaction time the actual rotational speed would overshoot, and system would be unstable. The implemented system is by no means the best possible, but it can be considered reasonable for the prototype.

8. TESTING AND ANALYSIS OF THE RESULTS

8.1 Implemented locomotion system

The testing of locomotion system had three different aspects; driving on horizontal surface, climbing obstacles and moving on inclined or vertical surface. By studying the system and its behavior it was possible to spot possible flaws and defects in the system.

Performance on horizontal surfaces was tested by driving on flat surface and around obstacles. The surface the robot was driving on was hard and had rough finish similar to fine or very fine sand paper. Agility and the use of different steering modes was tested e.g. by driving through gaps the robot would fit only sideways. The rocker-bogie suspension implemented works reasonably on horizontal surfaces. With multiple steering modes the robot is rather agile and has a great ability to move evading obstacles. However due to the speed of the robot and inaccuracy of the joystick control operating the robot is depending on the skills of the operator.

As the steering and controlling the robot is done entirely by the user, the performance of the horizontal driving is difficult to measure. However, the test revealed information about the structural design of the robot. Testing on horizontal surface revealed excessive flexibility in robot’s structure, which was addressed by redesigning rocker and bogie as the robot’s weight was able to twist them. Initially rocker and bogie had c-beam structure, with long side being 15mm and short 5mm and material thickness being 2.5mm. This was changed to a triangle shaped beam with 15mm triangle sides and wall thickness of 2mm.

Robots capability of climbing obstacles was tested by setting obstacles of different sizes on the path of the robot. The obstacles used were mainly box shaped, so the robot’s wheels had to climb vertical surfaces in order to pass them. Some of the obstacles were wider than the robot and thus affecting both sides of the suspension, but mainly the tests focused on obstacles affecting only left or right side of the robot as presented in Figure 34 with red box. This was chosen to represent the capabilities of the robot better, as it is more challenging. Situation with wide obstacle that affect both sides of the suspension was also seen as slightly similar to the floor to wall transition, which was tested later. The robot was also tested with multiple obstacles at the same time.

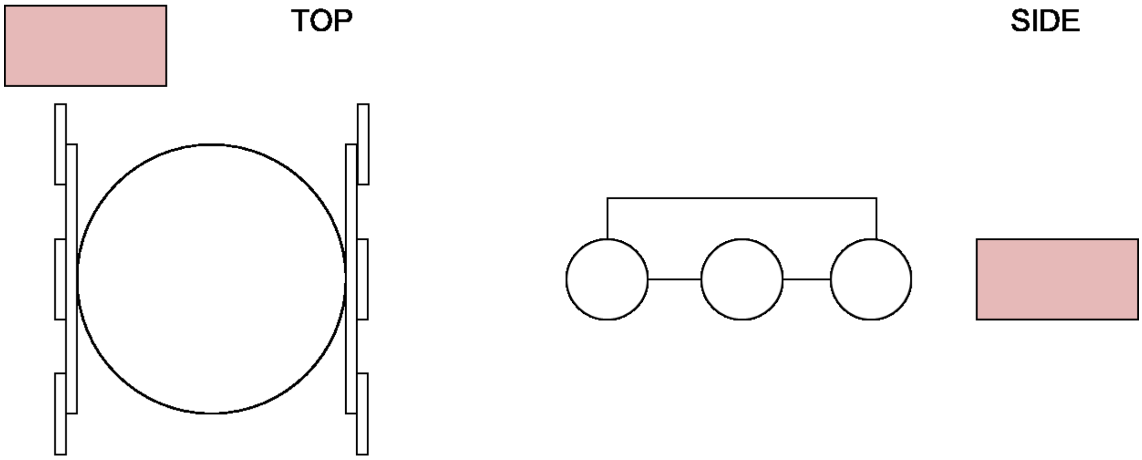

Figure 34. *Obstacle climbing*

The robot can easily pass obstacles smaller than half of the wheel diameter, in this case 3cm, but even larger obstacles are passable. Due to the ground clearance being only approximately 4cm, any obstacles larger than that risk the body touching the obstacle and getting the robot stuck. As each of the robot's wheels have their own motor, equal rotational speed cannot be guaranteed, and some of the wheels may slip or stall when encountering difficult obstacles. However due to the six wheel drive the robot is capable of moving in relatively rough terrain as seen in Figure 35.

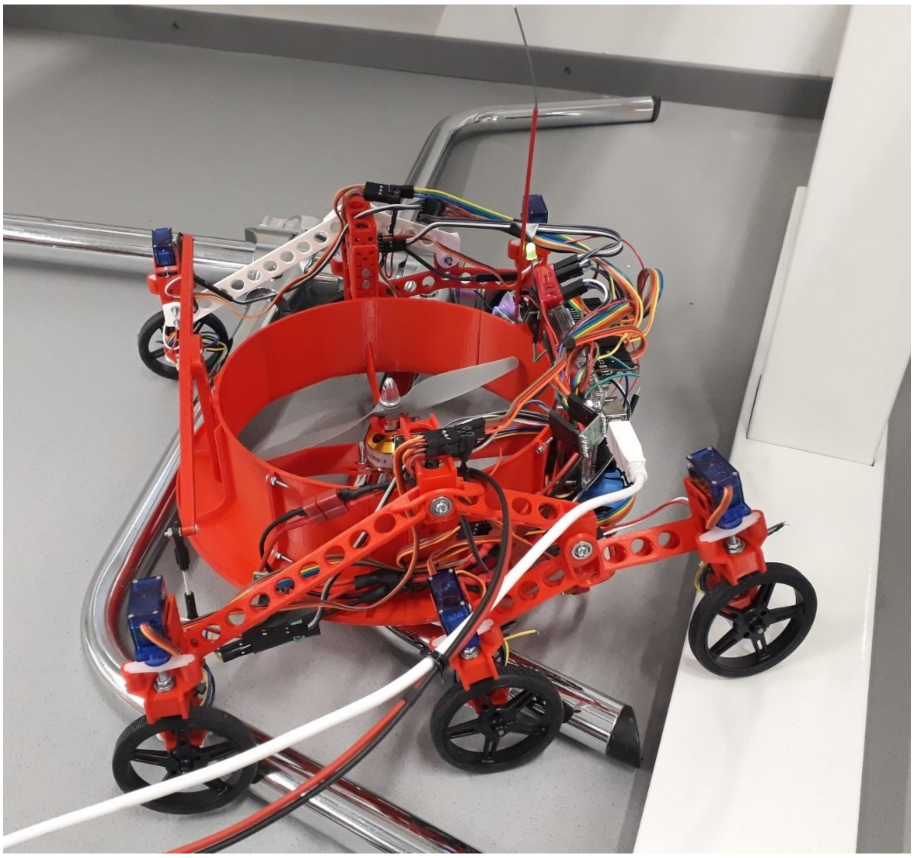

Figure 35. *Robot clearing obstacles*

The chrome pipes in Figure 35 have diameter of 2.5cm and some of those are partially lifted from ground increasing the total height to 3.5-4cm. However as most of the wheels still have contact with surface under them, the robot is able to move, even though some of the wheels would slip or stall.

If only one side, left or right, of the wheels is facing the obstacle, the robot was proven to be able to pass at least up to 8cm vertical obstacles. However, it is not able to do this if the front wheel is one of the two connected to rockers. As the rocker is connected to the robot's body, the body shall rise if rocker tilts. This will direct too high friction requirement for single wheel and the wheel is not capable of climbing over the obstacle. Instead the wheels may start slipping. When going bogie first, the suspension can move more freely, and the robot is able to maintain traction with most of the wheels, and therefore has better ability to lift the wheels on the obstacle.

One important feature of a wall-climbing robot is to be able to move between different surfaces, such as the transition from floor to wall. This was tested by driving the robot against a vertical surface. The horizontal surface was the same rough surface as used to test the robot's abilities on horizontal driving and obstacle climbing, and the vertical surface used was relatively smooth painted plane with similar surface properties to a painted wall. The testing was done both driving rocker ahead and bogie ahead in order to identify possible differences in robot's performance.

The robot is capable of moving between two surfaces with 90-degree angle, i.e. do the transition from floor to wall, when driving directly against vertical surface. However, with current design, it is only capable of doing the transition when moving rocker ahead. The trajectory of bogie is too wide, and instead of lifting the robot's body to wall, the bogies will tilt 90 degrees and lose traction as presented in Figure 36 A. As wheels in bogies lose traction the wheel pair connected to rockers is not strong enough alone to push the robot against the wall and increase the traction in bogies by pushing them against the vertical surface.

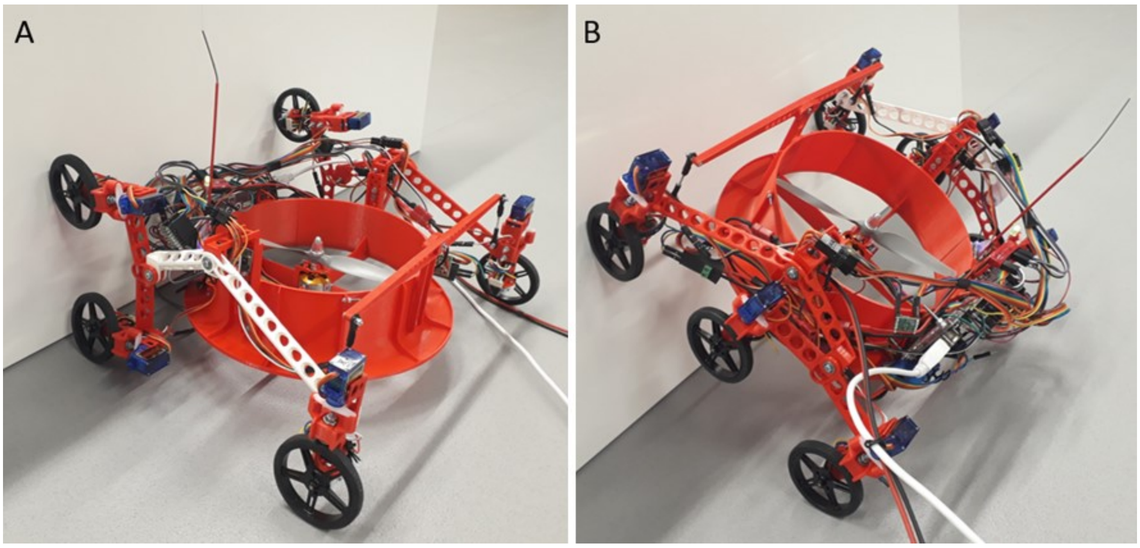

***Figure 36.** 90-degree transition A) bogie first B) rocker first*

When moving rockers ahead, the robot has better traction as only one pair of wheels is trying to climb the wall at first. The wheels in bogies maintain good traction, as most of the robot's weight is on them. Rockers will lift the robot's body, and in the process tilt the propeller more towards the wall. Hereby the propeller will be able to produce an adhesion force towards the wall and thus increase the traction on wheels in contact with the wall. The robot is also able to lift the wheels on bogies towards the wall, as seen in Figure 36 B, but without sufficient adhesion force it won't be able to climb and will fall when reaching 90-degree angle.

The capabilities on inclined or vertical surfaces were tested by placing the robot on a surface with similar surface finish to painted wall. The propeller was set on in order to produce an adhesion force that would increase the traction. However, on vertical surface this adhesion force was not sufficient. The performance of the drivetrain and suspension was observed in order to note abnormalities.

On inclined surface the robot is not able to stay still without any input from user control, unless positioned sideways. Due to the radius of wheels and the mass of the robot there will be enough torque in wheels to start rolling the robot downhill despite the 1:100 gearing in drive motors. Therefore, some voltage input to drive motors is required in order to keep the robot still. Unwanted rolling could be also solved by using smaller wheels and thereby decreasing the torque caused by the robot's weight, or by custom gearing, based on worm gear, in drive motors.

While testing adhesion on vertical surface, it was noticed that while trying to move upwards rockers ahead, insufficient adhesion can cause the middle wheels to rise and lose contact with the surface. Due to the geometry of rocker bogie suspension the rear wheel of bogie and mass of robot may cause bogie to act as lever, as presented in Figure 37, which will lift the middle wheel off the surface.

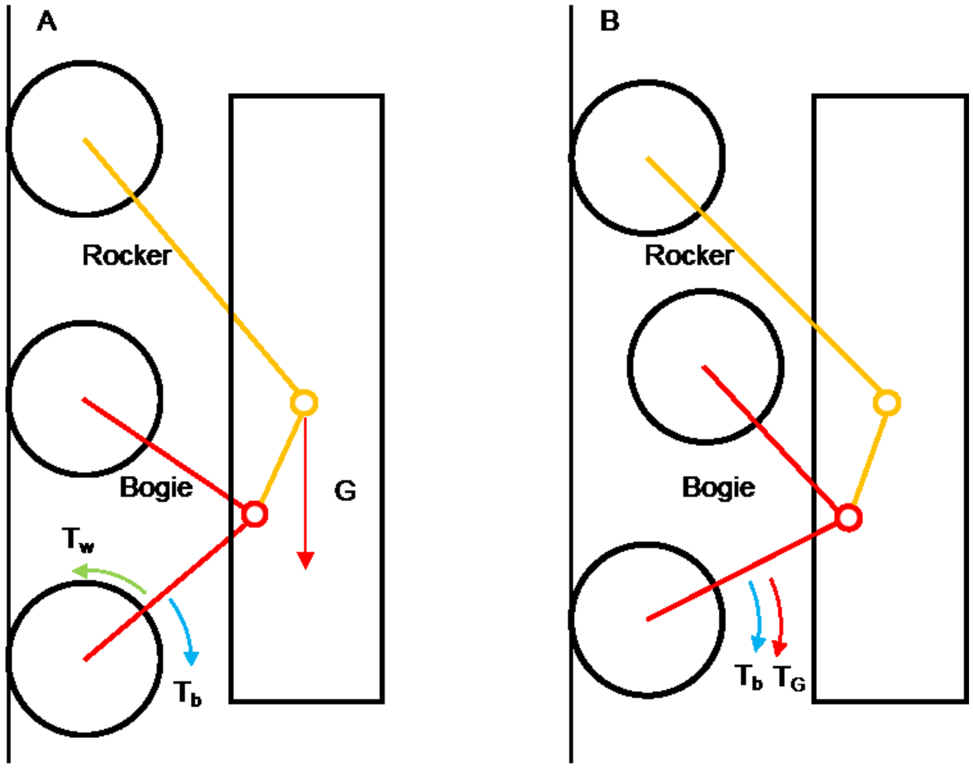

Figure 37. *Free body diagram of rocker bogie suspension on vertical surface*

The drive motor will cause to lowest wheel pair a torque T_w presented in Figure 37 A with a green arrow. This torque has equal opposite torque T_b, presented with blue arrow, in bogie arm presented with red. Also, the mass of the robot will cause force G to connection point between the robot's body and rocker, presented with orange. The force G can also be expressed as torque around the lowest set of wheels as presented in Figure 37 B with torque T_G. These torques seen in Figure 37 B will rotate the bogie and lift the middle wheels of the surface. Similar problem may also occur when moving bogie first, even though this doesn't seem as likely according the tests. When going bogie first the front wheel pair will be lifted while middle and rear maintain contact with surface.

When considering the limitations in crossing high obstacles moving rocker first, transferring from floor to wall bogie first and moving upwards on vertical surfaces rockers as leading part, these observations may indicate serious problems with the suspension when used in wall-climbing robot. As the focus of the thesis was not the implementation of rocker-bogie suspension but rather the adhesion method to be used with the suspension, these potential defects weren't observed before actual testing. However, it would be possible to address the things mentioned above by adjusting the rocker-bogie geometry. For example, in situation presented in Figure 37 by shortening or adjusting the angles of the bogie arms the lever affected by the gravity G wouldn't be able to induce as high torque around the axle of the lowest wheel pair. Also, sufficient adhesion force should push the suspension tighter towards the surface, and therefore keep the wheels in contact.

8.2 Implemented adhesion system

Initially the adhesion was tested simply by hanging the robot on string and testing whether enough adhesion can be achieved to move on vertical surface. With testing, things already suspected in chapter 7.4 became apparent; the achieved maximum propeller speed and therefore thrust is not sufficient to produce enough thrust and suction to hold the robot on wall. Therefore, another method was developed to inspect the capabilities of propeller and compare the empirical results to the theory presented in chapter 5.

Adhesion of the robot prototype was tested in practice on inclined surface. A painted surface, with seemingly similar surface finish properties as regular interior walls, was tilted against adjustable height as presented in Figure 38.

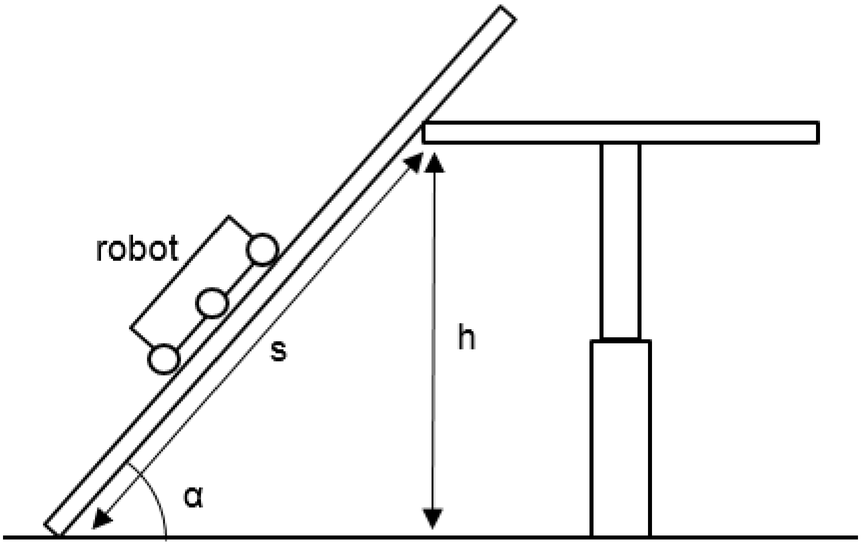

Figure 38. *Experimental setup for adhesion testing*

The length s was kept constant and the height h of the surface were measured in order to calculate the inclination angle α. Due to safety and practical reasons the robot was attached with string to upper end of the slope. Robots propeller speed control was set to manual and setting value was increased until the robot was able to drive up the surface.

Test could have been also done by finding the propeller rotational speed where the robot is able to stay still instead of sliding down the slope. Instead driving uphill was chosen as it represents the robots normal use more precisely. Driving will also reveal certain problems that may occur due to the locomotion system implementation. These were discussed in chapter 8.1.

The robot was connected to a PC in order to read the propeller rotational speed sensor. As the speed measurement value is not perfectly static, an average from the propeller

RPM values during the time robot was moving was calculated. These averages on multiple different angles were plotted in a chart with theoretical rotational speed required from propeller on similar inclination angles. This comparison can be seen in Figure 39.

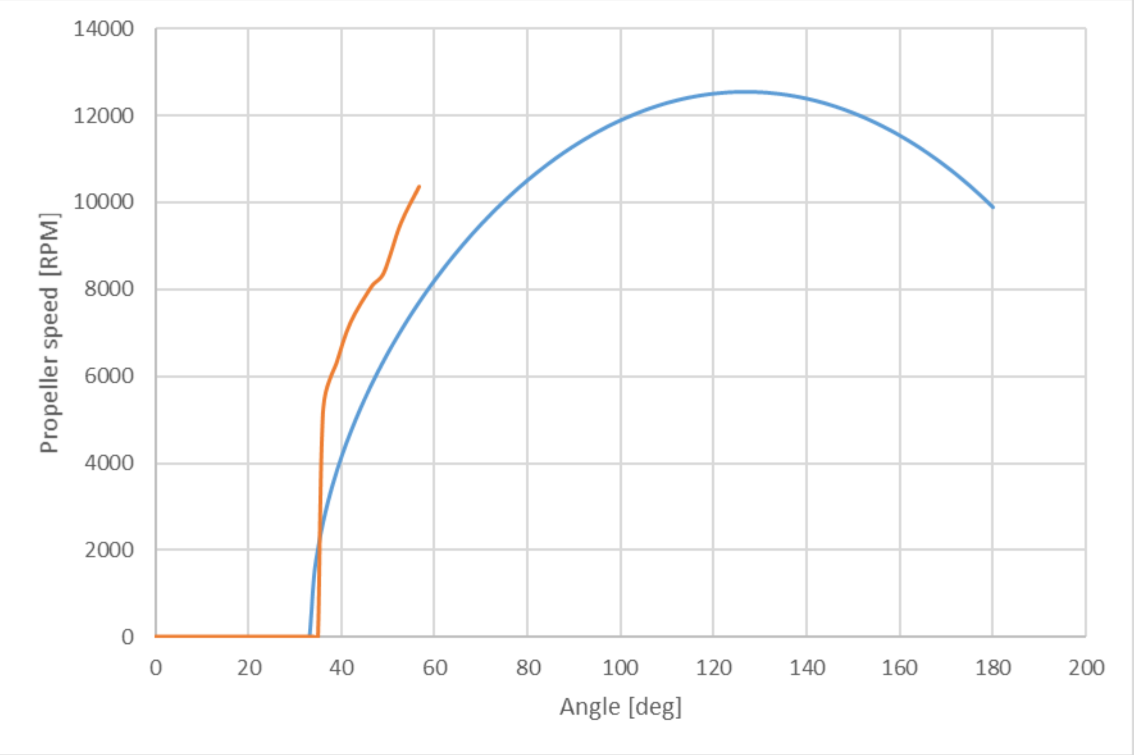

Figure 39. *Measured propeller speed compared to calculated propeller speed*

In figure can be seen that on measured angles the required propeller speed seems to follow similar path as the equation for required speed defined in chapter 5.2. There are clearly some losses that haven't been taken in account, as the actual required speed is higher than calculated theoretical value. There may be also some errors in theoretical values used for calculation e.g. the friction coefficient may differ due to dust sticking to wheels.

According to Eberhardt and Anderson [12] plane propellers work approximately on 84% efficiency. Some of this efficiency loss can most likely emerge as smaller change in the air velocity over the propeller, and therefore the equation (6) should take the propeller efficiency in account. Also, the duct may not work as efficiently as assumed in chapters 3.4 and 5.2. At least if the airflow produced by the propeller is lower, the suction induced by the duct will be smaller as well. If total efficiency of 75% for adhesion method is assumed, the theoretical value would follow the measurements more closely, as presented in Figure 40.

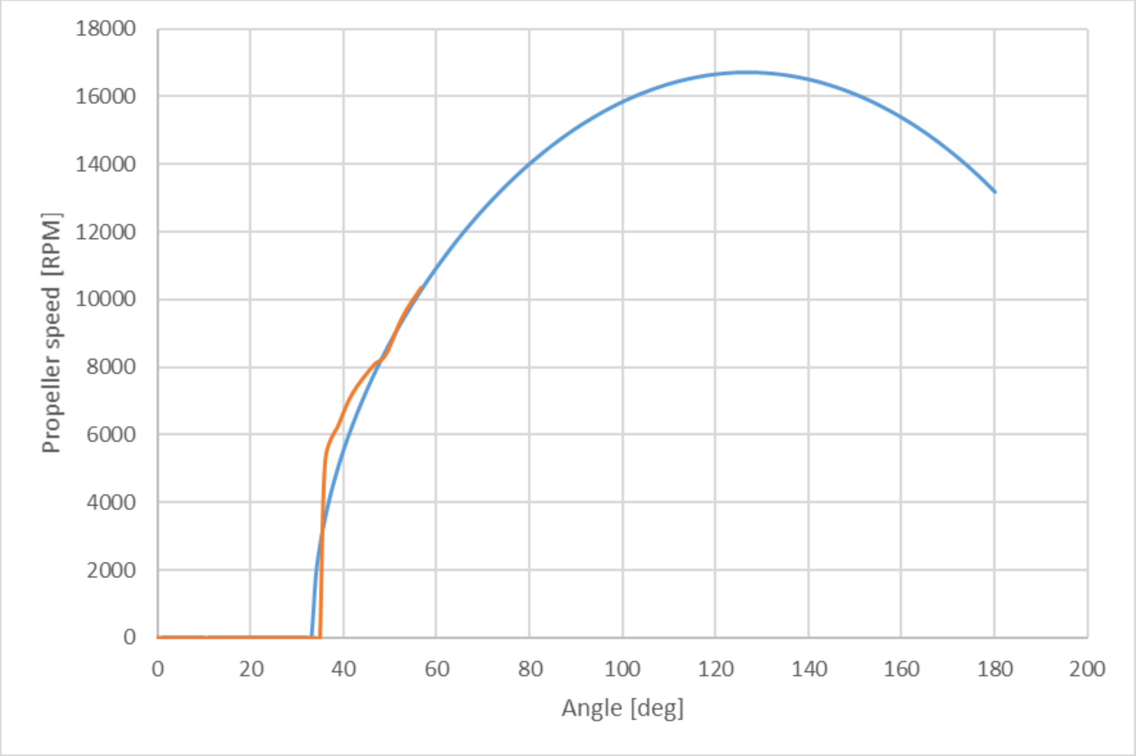

Figure 40. *Measured propeller speed compared to calculated propeller speed with 75% efficiency*

Here the overlapping of curves is considerably better than what is seen in Figure 39. However due to the limitations in maximum angle measured it is impossible to say whether the rest of the theoretical curve would represent the real world reliably. The measurement data should reach preferably at least the angle of 130-135 degrees in order to see whether the maximum force and the shape of the curve follows the theory presented in chapter 5.2.

According the performance seen in tests and equation (5), in order to reach reasonable adhesion force either motor capable of higher rotational speed or larger propeller with similar rotational speed as seen in prototype would be required. As mentioned in chapter 7.4, there are certain limitations on components commercially available. With further testing, it might be possible to find a motor and propeller combination that would work better, but by increasing the component size, it is also possible to increase the robot weight disproportionally to the adhesion force capability increase. Optionally also increasing the portion of suction induced by the duct in the adhesion force could be increased by lowering the duct. However, this would decrease the ground clearance and therefore work against the original idea and design requirements of the robot.

8.3 Future development

As the adhesion was deemed insufficient, further research would be required in order to solve the problems found with the prototype and develop a fully working wall-climbing robot with high ground-clearance.

Information provided about commercial products similar to the ones used in this experiment may be insufficient, which complicates the design process. Therefore, further empirical testing about performance would be required to define whether current design concept could be used with different components. Testing could also provide further insight on the correspondence of theory and practice, and for example possible differences between equations, such as (5) and (6), and practice could be revealed. This would be important, as it was found during the testing of the adhesion system, that the theory presented in this thesis does not entirely correspond the performance seen in prototype. This is most likely due to efficiencies of components used that weren't taken in account in theory.

Overall more research should be done on possible adhesion methods and their implementations. Results received in this thesis indicate problems with keeping the adhesion system size small if based on thrust mainly. Further research on components could reveal whether the insufficient adhesion could be solved by upscaling the adhesion system size, or entirely new approach would be required e.g. by increasing the propeller area with an additional propeller, ending up with similar solution seen in VertiGo. It might be also possible to use entirely different adhesion method but depending on the method this might require some compromises to be made regarding the design requirements. Such techniques might include solutions like suction cups attached to wheels or tracks, which might be capable of higher adhesion forced, but also introduce some complexity to the system and limit performance on rough surfaces.

One of the problems that would emerge more clearly if testing was done on multiple different surfaces would be the variations in friction coefficients between different materials. In this thesis a single value was used based on measurements, but even then, the testing indicated some variables, such as dust sticking to wheels, affecting the actual value. In order to optimize the adhesion force the effective friction coefficient should be known. It might be worth surveying whether friction coefficient, and therefore required adhesion force, could be measured either with internal or external sensors measuring whether the robot is slipping on the surface.

Certain problems were also noticed in rocker-bogie during testing. Due to geometry and overall design the suspension has different capabilities depending on moving direction and whether the surface is horizontal or vertical. Unless entirely new suspension to ensure the traversing abilities on different surfaces is designed, further analysis of rocker-bogie performance on vertical and angled surfaces would be required. The suspension properties and performance can be affected with suspension geometry, yet the exact effects are not known. Therefore, either empirical research or theoretical simulations would be needed to explore the effects of geometry on wheel traction on different angled surfaces.

It could be also beneficial to research entirely different locomotion options offering possibility for high ground clearance or good traversing abilities on rough terrain. Some solutions may have certain limitations, e.g. top speed, suspension travel or effective contact area, but the overall locomotion system is a compromise between different properties.

The suspension of the prototype tested in this thesis formed a great part of the robot's mass and minimizing this mass would decrease the adhesion force required. Some of the mass cannot be affected as there are no significantly smaller or lighter components available to replace e.g. the drive motors, and he main structure is 3D-printed PLA plastic, which in itself is a light material. However, it could be beneficial to research whether some of the structure could be replaced with e.g. carbon fiber profiles, and whether such structures could either increase or at least maintain the structural durability of the robot. Similar research on used materials and structures could be also done for the adhesion system. Even though the weight savings wouldn't be significant, they could increase the performance of the robot increasing the maximum climb angle.

8.4 Additional requirements for design from test results

Based on the observations done in empirical tests couple new design criteria could be added to the resign requirements presented in chapter 4. These requirements focus mainly on safety perspective of wall-climbing robots. They may seem obvious, but due to the importance in this application they were seen as worth mentioning.

- **Structure robustness**

Due to the adhesion being based on rotating propeller the structure should be able to withstand constant vibrations and sudden forces caused by the propeller. This is basic fundamental criteria in machine building and design, but in a robot where reliability is extremely important for safe operation some additional attention should be considered in the design process. Chosen materials and structural solutions should be considered so no fatigue will appear over the lifetime of the robot, or fatigue can be detected in periodical inspections before it can cause trouble for the robot's operation.

While testing the prototype it became apparent that especially connections utilizing bolts and nuts have high risk of separating due to the constant vibrations caused by the propeller. This could be solved by slightly different design locking the nuts tighter in position, by use of nylon nuts or alternatively thread locking fluids. The vibrations also affect wire connections like the 2.54mm crimp connectors used due to prototyping nature of the robot.

- **Structure shielding**

As the adhesion is thrust generated by large propeller area there is a high risk of small debris from the surface ending up in the propeller. When coming in contact with the propeller the debris may be a risk for the robot itself and for the environment and people around the robot as they may leave the propeller area on high velocity.

Effort should be made in order to reduce the possibility of debris ending up in propeller, and therefore reducing the risk of small particles flying in high speed away from robot. This could be probably implemented with some kind of shielding or mesh around the propeller allowing the airflow, but stopping any harmful particles entering the propeller area.

- **Locomotion stability on inclined surfaces**

This requirement is related to the requirement of being able to move omnidirectionally but considered as worth being a separate requirement. As the prototype revealed, great traversing abilities and obstacle crossing capability on horizontal surface may not guarantee similar capabilities on inclined surfaces if sufficient attention hasn't been paid to the locomotion device design.

In addition to being able to induce sufficient adhesion force for all surfaces and orientations the robot can end up, also the operation of the locomotion system should be considered in different orientations. If the effects of the forces affecting the locomotion system change as the orientation of the robot changes, the robot or its structure should be able compensate or minimize any adversary effects.

Here the focus was mainly on the adhesion system, but the robot should be considered as a combination of locomotion and adhesion systems. As the robot's mass affects the suspension differently on angled surfaces, the geometry should have been designed differently in order to minimize adverse effects of the weight of the robot's body.

9. SUMMARY AND CONCLUSIONS

The purpose of this thesis was to define and use a design criteria to assess and compare concepts of wall-climbing robots with high ground clearance. Three different adhesion system concepts utilizing rocker-bogie suspension were considered and these were compared according the criteria created. Rocker-bogie suspension was chosen due to structural simplicity and good performance seen in planetary rover robots implemented by NASA. The concept seen as the most feasible was implemented as physical prototype robot. The capabilities of this prototype robot were tested focusing on the two main features of a wall-climbing robot; locomotion and adhesion system. Due to the insufficient adhesion force, the prototype does not work as an actual wall-climbing robot, but rather as a rover with increased climbing abilities.

The prototypes locomotion system was deemed reasonable on horizontal surfaces. The robot was able to pass different obstacles of variable size, yet due to the 4cm ground clearance, the robot's body may get stuck even if the suspension would be able to cope with the obstacles. Certain problems with insufficient motor torque and traction were noticed when trying to move to and on vertical surfaces. Some of these problems are related, and therefore solvable, to the geometry of rocker-bogie suspension and insufficient adhesion. Some were also related to the direction the robot is moving. The geometry of rocker-bogie suspension implemented seems to have different capabilities depending on whether the robot is moving rocker or bogie ahead and may not be able to pass certain obstacles if either rocker or bogie is at the leading end of the robot depending on situation.

The robot was found unable to move on vertical surfaces. However, it was able to move on inclined surfaces of up to approximately 55 degrees, which is already a noticeable increase as without any additional adhesion force the robot would be able to move on surface with approximately 30 degrees angle. Limited performance on inclined surfaces was found to be mainly due to the propeller being unable to reach the rotational speed required, but also due to the neglect of the efficiencies in forming the theory used.

Overall implementing a wall-climbing robot with good ground clearance was found to be a challenging task. There are certain problems with the adhesion system and weigh to power ratio management. Pneumatic adhesion methods seem the most versatile and suitable for different surfaces, as the technology is relatively mature, and they do not rely on specific surface materials.

The most used pneumatic adhesion method, suction, is relying on ground clearance and sometimes on surface smoothness and is therefore problematic. It is difficult to achieve high adhesion force based on suction without small ground clearance, as very high air flow would be required, and limitations of used motor have to be taken in account.

The other pneumatic adhesion method, thrust, is requiring either large area from the propeller, or high rotational speed of the motor. As seen in the prototype implemented this can be difficult to achieve in reasonable scale; the 7inch propeller filling approximately 30-45% of the whole robot's area, was not capable of inducing sufficient adhesion force even when complemented with suction from duct. Either propeller size should be increased, or motor changed to a faster one. If the propeller size is increased also the suspension dimensions have to increase. This will increase the weight, which will in turn may require sturdier components to keep the structure stiff enough.

The motor power and available rotational speed could be potentially increased. However most of commercial products capable of higher speeds are intended for smaller propeller area and may not be able to reach their maximum speed reliably with larger propeller. Without practical testing of the actual performance the motors capabilities are difficult to estimate, as the information presented is often limited or lacking. More powerful motors are also heavier than the one used in robot prototype. Due to higher current rating they would also require better ESC, which again means increase in weight. As decision was made to leave the battery as separate unit outside the robot, higher requirements for power supply won't increase the robot's weight.

Electro adhesive and chemical adhesion methods might offer solutions and possibilities regarding combining the adhesion method in to the locomotion system instead of using space in the area that could be used for additional actuators for example. However, based on the review of the state of the art these methods and technologies may not be mature enough to be used in a robot similar to the prototype developed here.

Even though the outcome of the thesis was not a fully working wall-climbing robot with reasonable ground clearance, this thesis has provided useful information regarding design process of such robots. Based on the information presented in this thesis the focus in design process can be dedicated to important aspects presented. At minimum certain design solutions can be avoided or preferred according their properties and capabilities, and future research can be aimed to the direction seen as most potential.

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