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A Robot Locomotion Mechanism Powered by Wind Energy:  
WANDER-Bot

SCHOOL OF AEROSPACE, TRANSPORT SYSTEMS AND  
MANUFACTURING

MSc ASTRONAUTICS AND SPACE ENGINEERING  
Academic Year: 2024 - 2025

Supervisor: Saurabh Upadhyay  
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the degree of MSc Astronautics and Space Engineering

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## **Abstract**

This report discusses the experimental development of WANDER-Bot: an early mechanical locomotion solution design concept for planetary exploration. It requires low-cost, low-power, low-storage, and is designed to be easily manufactured and assembled onsite using ISRU manufacturing methods. It is a design proposal which aims to address the existing limitations of space robotic missions and locomotion solutions: their high-cost, power budget constraints caused by degrading solar and RTG power sources, large storage requirement for transportation on the launch vehicle, high complexity, and difficulty to maintain and repair. Titan has been proposed as the future planetary environment exploration application for the system.

The WANDER-Bot integrated system is composed of 3 main mechanisms: a Savonius turbine wind energy capture mechanism, reduction gearing mechanism to multiply torque, and a Jansen legged walking mechanism for locomotion. The robot uses simple mechanical linkages and assembly methods to lower cost and improve maintainability. Its 3D printable design allows future ISRU manufacturing potential, and its wind-powered driving mechanism offsets the electrical power demand for locomotion. Developed with consideration of planetary environments such as Titan, WANDER-Bot demonstrates the ability to walk forward in omnidirectional wind conditions, on rough, firm terrain at relatively low windspeeds, with a Titan-equivalent weight offset.

This report covers the design evolution of the integrated robot system, through prototype iterations, of its individual constituent mechanisms. It documents the challenges faced, design improvements, and performance analysis through the experimental testing campaign. Experiments include walking gait analysis to ensure locomotion smoothness and stability, verifying motion simulations, turbine RPM performance at different windspeeds, and the self-start threshold windspeed for each integrated system iteration. It documents how these experimental findings informed design changes in future iterations. Successes and limitations of the design and testing is identified, along with future improvements to increase performance and environmental representation.

The report concludes that this early WANDER-Bot prototype is not yet applicable for the environment in its current state, but the system demonstrates the feasibility of the low-cost, wind-powered, additively manufactured, easily maintainable locomotion solution. Future work is proposed to take this design further to develop maturity for the proposed application, such as steering mechanisms, variable speed control, and basic robot perception and autonomy for obstacle avoidance.

**Keywords:**

Jansen mechanism, Titan planetary exploration, Savonius wind turbine, low-cost, ISRU, Experimental testing and development.

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## List of Abbreviations

|            |                                                                  |
|------------|------------------------------------------------------------------|
| AREE       | Automaton Rover for Extreme Environments                         |
| CU         | Cranfield University                                             |
| DoF        | Degrees of Freedom                                               |
| EOL        | End-of-life                                                      |
| HAWT       | Horizontal Axis Wind Turbine                                     |
| ISRU       | In-Situ Resource Utilisation                                     |
| JPL        | Jet Propulsion Laboratory                                        |
| MMTRG      | Multi-Mission Radioisotope Thermoelectric Generator              |
| NASA       | National Aeronautics and Space Administration                    |
| PLA        | Polylactic Acid                                                  |
| RPM        | Rotations per Minute                                             |
| RTG        | Radioisotope Thermoelectric Generator                            |
| VAWT       | Vertical Axis Wind Turbine                                       |
| WANDER-Bot | Wind Actuated Navigator, Discoverer, Explorer and Research Robot |

# 1 Introduction

This chapter covers the background and motivation of the project, identifying the need for low-cost, naturally powered locomotion systems, in planetary robotic exploration applications. The project will consequently aim to experimentally develop an early design concept this, WANDER-Bot (Wind Actuated Navigator, Discoverer, Explorer and Research Robot), with iterative prototype and testing.

## 1.1 Background

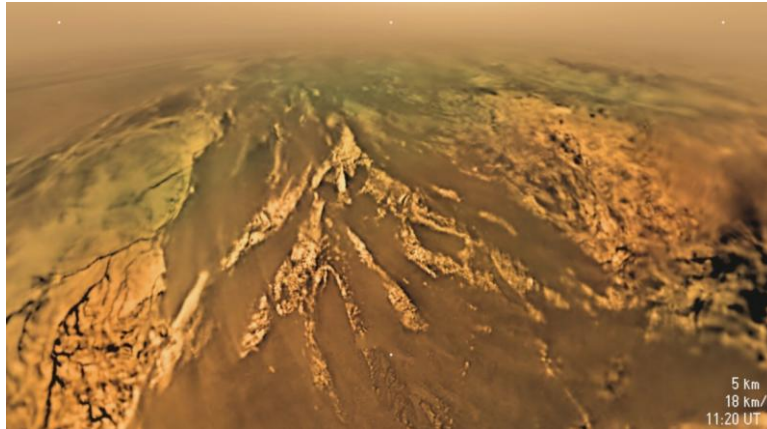
For decades, planetary robots have been used at the forefront of space exploration, opening our understanding of other planetary environments and their past, and events that shaped and transformed them over the ages to their current conditions. Robotic missions have produced invaluable data which have enabled us to better understand their geological landscapes, terrain, and atmospheric conditions, being an asset in our search for the possibility of extra-terrestrial life.

However, existing robot solutions have largely been constrained to using electrical power sources, such as RTGs and solar cells, for wheeled locomotion. The challenges of these electrical power generation and locomotion solutions are that the systems degrade over time, are expensive to develop and operate, require storage methods for transportation, and are difficult to maintain and repair. The degradation of these electrical systems in hostile planetary environments are often the limiting factor to the EOL of a planetary robotic exploration mission.

Developing ISRU-friendly fabrication methods in the future would reduce the space requirement for transportation in space robotic exploration missions. Using simplified mechanical links would reduce mission cost and increase the robustness of locomotion systems in hostile environments, and make them easier to maintain and repair. Harnessing natural energy such as wind directly for locomotion would allow the robot to offset its electrical power budget for mobility, allowing more power to be utilised for payloads, extending mission EOL, or allowing more capable sensors to be used.

While applicable to multiple planetary bodies with wind, this project will investigate the future application of the system on Titan, the largest moon of Saturn, as a test case scenario. It is an environment which holds very high scientific value for future exploration, due to some of its striking similarities with Earth. It is the only other known body in the solar system which has stable liquids on its surface, made of methane and other organic compounds, the building blocks for potential life. It has a nitrogen-rich atmosphere much denser than Earth's, and experiences weather cycles similar to Earth's hydrological cycles. Geological features such as dunes, valleys, and cryovolcanoes, shaped by weathering, make it a dynamic and evolving world. Its thick atmosphere naturally shields the surface from much of the radiation, and it may be a viable candidate for hosting life which functions based on hydrocarbons instead of water. Studying Titan would also allow us to understand planetary evolution and climate systems under different conditions.

The most prominent past missions to Titan include the Voyager 1 flyby in 1980 which gave us the first close up look at Titan, revealing its dense Nitrogen-rich atmosphere and thick haze that obscured the surface. The Cassini-Huygens probe in 2005 is the only landing on its surface. During the descent and landing, the probe revealed its Earth-like terrain features, as shown in Figure 1-1, its atmospheric conditions, and its molecular composition. The upcoming Dragonfly rotorcraft will aim to deepen our understanding of the moon further; the mobile explorer will take advantage of the dense atmosphere and low gravitational field strength for its flight between multiple landing sites. (Elachi et al., 2005) (Zarnecki et al., 2005) (Johns Hopkins University Applied Physics Laboratory, 2025).



**Figure 1-1 The surface of Titan, as captured from Huygens (ESA, 2015)**

## **1.2 Motivation**

The motivation of this project is to conduct a research investigation into the feasibility of an explorer robot locomotion design concept, for future Titan exploration, which addresses the challenges faced by existing planetary robots. It will propose a naturally powered mechanical locomotion design solution, using Jansen-inspired linkages. It should have easy on-site assembly to reduce storage requirement for transportation, and the components of this locomotion system should be easily fabricated using additive manufacturing methods such as 3D printing, making it inherently friendly for future ISRU operations, further reducing transportation storage requirement. Using this approach also allows multiple robots to be manufactured for a low-cost, fast exploring robot swarm.

Having simple mechanical linkages allows ease of assembly, maintenance, repair, and provides robustness of the mechanism in the hostile planetary environment. Allowing the mechanism to be directly powered by a wind energy capture mechanism eliminates the requirement for electrical power to operate the system and drive the robot, allowing power budget offload for locomotion. The robot should be designed to be able to walk forward in typical conditions expected to be found on Titan, based on atmospheric and environmental condition data returned from the Huygens probe.

## **1.3 Project Aims and Objectives**

### **1.3.1 Project Aim**

Investigate and experimentally develop an early design concept for a fully mechanical robot locomotion design, suitable for future ISRU operations, using simple Jansen-inspired linkages. The system shall be powered directly by wind energy and be able to walk forward regardless of wind direction, using the Titan environment as one of the test case scenarios. The integrated system will consist of 3 constituent parts – the wind energy capture mechanism, gearing mechanism, and Jansen locomotion mechanism.

### **1.3.2 Project Objectives**

1. Conduct a literature review to:
  - a. Identify existing power generation methods and their limitations.
  - b. Research existing planetary locomotion solutions, identifying their limitations with regard to power consumption, cost, ease of transport, robustness, and ease of maintainability.
  - c. Identify existing missions and future mission proposals which use air as a medium for locomotion, or use the Jansen mechanism for planetary exploration.
  - d. Identify features and ratios of the Jansen mechanism, current applications and research work, and how to optimise the mechanism for smooth linear walking motion with maximum stability and minimal resistance.
  - e. Identify the atmospheric conditions of Titan, and carry out calculations to determine methods to replicate these conditions on Earth for testing and development.
  - f. Identify the knowledge gap and contribution of the project
2. Identify and generate design drivers and requirements for the system, as well as project constraints.
3. Produce a prototype of the Jansen locomotion mechanism, wind energy capture mechanism, gearing mechanism, and integrated system which allow smooth and stable forward movement regardless of wind direction.

4. Test the performance of the walking mechanism, wind capture mechanism, and integrated system prototypes, assessing their ability to operate in different windspeeds and directions. Study the data to make informed decisions on design improvements for future iterations. Propose improvements to increase representation of the Titan environment scenario.
5. Evaluate effectiveness of the design against aim and propose future considerations to mature the robot design and make it more capable for Titan and planetary exploration.

## **2 Literature Review**

This chapter aims to cover objectives 1a to 1f. It investigates existing power source and locomotion solutions for planetary robots and their limitations, as well as future mission concepts utilising wind for locomotion. It also investigates the Jansen mechanism, its applications and current studies, and environmental conditions of Titan, as this has been selected as the prime candidate for future application for this robot system solution. From the research, the chapter identifies a knowledge gap, proposing the thesis contribution to investigate potential solutions.

### **2.1 Existing Energy Source and Locomotion Solutions for Current Planetary Exploration**

All surface level robotic planetary explorations to date have relied on 2 main forms of power generation for system operation: solar power from photovoltaic cells, and RTGs.

The NASA Perseverance and Curiosity Martian rovers have a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which generates 110 W of nominal electrical power at the start of the mission. RTGs continually generate power and heat due to the uninterruptable radioactive decay of Plutonium-238. Much of this energy is used for the continual operation of onboard systems such as computation and OBDH, thermal control, communications, scientific instrumentation, and locomotion. However, some operations can have an instantaneous power demand which far exceeds the maximum power output of the RTG; for Perseverance this can peak as high as 900 W when conducting science experiments. Locomotion also consumes a significant amount of power to move the robot to new locations. To resolve this, a proportion of the power generated from the RTG is used to charge 2 lithium-ion batteries which provide the higher power demand needed for scientific studies and locomotion. (NASA, 2020) (JPL, 2020).

A drawback of this power budget is that different operations have to be ordered sequentially based on priority in the given instance. Continual locomotion would

not be possible, as it would consume a disproportionate amount the power required to operate other robot systems, reducing the scientific value and quality of the mission.

Solar panels have also been used on rovers such as Spirit and Opportunity. They work in a similar fashion to RTGs, supplying direct current to onboard systems, and charging batteries to draw power during night time or during operations where power demand peaks. (NASA, 2017).

Both methods face limitations, as nominal power can only be generated at the start of the mission. Therefore, they have to be sized based on the power demand expected near to mission EOL. RTGs undergo a predictable exponential half-life decay as the Plutonium-238 capsules deplete. Solar panels also undergo degradation from outgassing, erosion, dust accumulation, and Gallium Arsenide decomposition. Due to performance losses as the mission progresses, each year certain instruments and robot capabilities have to be switched off to prioritise other systems. For locomotion, this also means that the robot travels reduced distance with each year that passes, as its power budget gets compromised in favour of other mission systems, further limiting its range. (NASA, 2020) (Schmitz, 2020) (Lorenz et al., 2021).

Harnessing natural energy sources such as wind to drive locomotion directly through mechanical linkages removes the inherent degradation factors of electrical components. By almost completely offloading the power demand for locomotion, it allows mission life to be extended, or allows higher capacity payloads to be used.

Missions such as Perseverance are high cost, amounting to \$2.7 billion (The Planetary Society, 2020). A significant portion of this will have been to develop a resilient locomotion solution, designed to operate in the hostile environment of Mars. Despite development and testing, it was found during the mission that the wheels were cracking and becoming severely damaged, as shown in Figure 2-1, due to material fatigue caused by the rough terrain, compromising locomotion performance. This design flaw was rectified for the later Perseverance mission. (BBC, 2024).



**Figure 2-1 Wheel damage on the Mars Curiosity Rover (BBC Newsround, 2024)**

Both Mars robot missions were launched by the Atlas V launch platform (as seen in Figure 2-2), being its sole payload. The chassis, locomotion system, and power generation system occupy a significant part of the robots' mass and volume footprint. (Spaceflight Now, 2025).



**Figure 2-2 Perseverance enclosed in Atlas V aeroshell (Spaceflight Now, 2025)**

## **2.2 Previous and Future Proposal Missions Utilising Wind for Locomotion**

To date, there have been no planetary robot missions which have utilised wind energy as a means to directly power locomotion. The Ingenuity Martian flying demonstrator used wind as a medium for moving from place to place. Its contra-rotating propellers, driven by electric motors, were powered by a battery which was charged using solar power (Balaram et al., 2021). The upcoming Dragonfly mission, currently scheduled to launch in 2028, is a RTG powered rotorcraft, designed to study Titan's surface and atmosphere. Being a standalone spacecraft mission, it is significantly larger than Ingenuity and will feature several design improvements based on lessons learned from the Ingenuity demonstrator mission. (Mcquaide et al., 2023) (Johns Hopkins University Applied Physics Laboratory, 2025).

Mission concepts which propose wind-powered locomotion include the Tumbleweed Mars rover, which is a 5 m diameter sphere featuring tetrahedrally arranged sails to optimise air resistance and increase ground coverage. Solar cells on the robot provide power for light sensors such as barometers, hygrometers, and high-resolution cameras. As wind pushes the robot directly with no torque multiplication, it means that large sails have to be used to drive the locomotion. Consequently, its inherent lightweight design means that heavier, more capable payloads cannot be used. (Tumbleweed Mars, 2024).

Project AREE (Automaton Rover for Extreme Environments) was a NASA project proposal to design a rover to operate on Venus, shifting from electronics to a fully mechanical system for computing and locomotion. One of the locomotion concepts featured a turbine powering a Jansen-inspired linkage for locomotion, and energy storing springs. An idea was to use mechanical clockwork mechanisms due to the harsh environment, extreme temperatures, pressures, and corrosive chemical compounds in its atmosphere, which electronic components have minimal resilience against. It was ultimately decided that the mechanism would be too unstable in extreme rocky terrain, and tank treads were

proposed as an alternative. To power the system, one of the ideas was to use a Savonius wind turbine, but this never reached maturity. (Sauder et al., 2017)

The Zephyr mission was a NASA concept for a robotic Venus lander designed to explore the surface using land-sailing, propelled using a wind sail and wheeled locomotion. While theoretically able to wander freely under wind propulsion, it was speculated that it would be only be able to land-sail for about 15 minutes per day, due to constraints in communications and data analysis. Facing multiple challenges with its electronics in the extreme harsh environment of Venus, Zephyr was only proposed to have a short mission life, returning 2 Gb of scientific data over a 30-day period. (Landis et al., 2019).

From the project proposals and exiting missions discussed above, it is evident that using wind is a tangible natural source of energy to drive locomotion systems. Purely mechanical locomotion solutions show advantages in hostile environments, being more resilient against extreme temperatures, pressures, and in the presence of corrosive chemical compounds. However, a lack of electronic systems also means they lack complex steering mechanisms to guide them accurately along a predetermined path, leading to a wandering behaviour.

## **2.3 The Jansen Mechanism**

The Jansen linkage was designed by Dutch Artist Theo Jansen as a means of converting rotary motion into linear forward movement through legged locomotion. With only a single degree of freedom, it is composed 13 different link elements, where the ground contact foot walking gait is defined by the relative ratios between the links. Jansen optimised the link ratios using a program written in 1990, which led to a final outcome which delivered smooth walking motion appearing as a mound or teardrop shape with a flat base (where the main traction and drive comes from) and high ground-contact time to deliver maximum stability and traction before the next step. (Strandbeest, 2025).

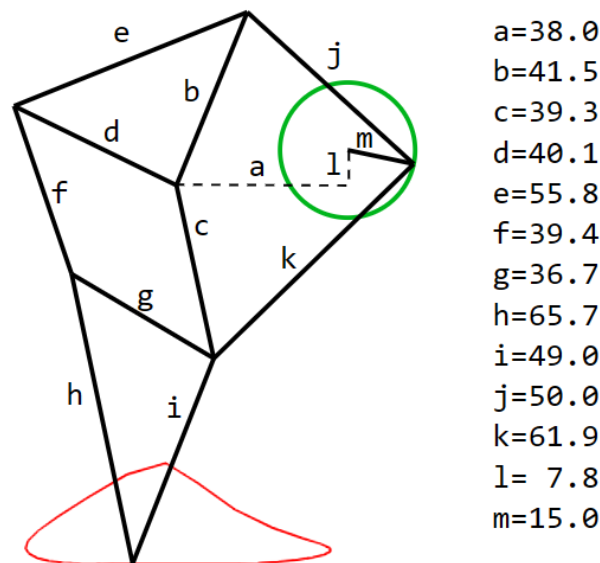
Since the 1990s, he built kinetic wind-driven sculptures known as Strandbeest (seen in Figure 2-3) which used the Jansen linkages, powered using wind sails. They have 3 pairs of legs on each side, each pair rotating in phase but offset by

an angle of  $120^\circ$ . This ensures stability of the robot, as it allows at least 1 leg in each corner of the robot to assume a supporting stance, taking the weight load. Still composed of crude materials such as PVC piping, cable ties, and pressurised plastic bottles for energy storage, these Strandbeests have since undergone several design evolutions which has made them able to mechanically react to the environment around them and become increasingly independent. The purely mechanical system has shown good performance for locomotion sandy terrain, and demonstrated excellent resilience in the harsh conditions of marine saltwater environments, namely temperature changes, weather events, and general degradation. Even with structural failure, the simple mechanical link design allows easy and low-cost repair before operation can resume. However, existing Strandbeest models to date can only walk when the blowing wind is behind it, in favour of its walking direction. Its windsail-driven nature makes it unable to move forwards in omnidirectional winds. (Strandbeest, 2025) (Sengupta & Bhatia, 2017).



**Figure 2-3 The Strandbeest, using Jansen linkages (Strandbeest, 2025)**

The link ratios for optimal smooth walking gait of the mechanism are shown in Figure 2-4.



**Figure 2-4 The Jansen Linkage Ratios (Analytic Physics, 2020)**

The mechanism has since been studied in detail to analyse its walking patterns, and has seen some research-based applications in robotics and mechatronic fields.

Mohsenizadeh & Zhou, 2015 carries out a kinematic analysis and simulation of Theo Jansen mechanism, studying the profiles traced by each of the joints, the instantaneous velocity, and time taken to cover each section of the cycle. (Mohsenizadeh & Zhou, 2015).

Patnaik & Umanand, 2016 also carries out kinematic analysis of the Jansen leg mechanism, and proposes a dynamic model using a bond-graph approach. The paper studies node trajectories and velocities, structural stresses, as well as the motor torque profile to operate each cycle at the crankshaft, assuming a constant motor angular velocity. The simulation also found that with a crank length of  $l_0$ , the foot profile step distance was  $4.5l_0$ , and maximum step height was  $1.5l_0$ . Verification of this data was conducted through independent simulation and experimental testing (see section Experimental Analysis of the Foot Profile). (Patnaik & Umanand, 2016).

Kavлак & Yongul, 2022 simulates the Strandbeest walking mechanism to overcome concave and ramp type obstacles, proposing a walking robot design.

It also analyses the effect of changing the link ratios on the walking gait, making it more suitable for curved profiles. (Kavлак & Yongul, 2022).

Sengupta & Bhatia, 2017 investigates existing applications of the mechanism, but concludes that most applications are at proposal, and prototype levels. It finds no known case studies of its application for real-life applications. It however concludes that the mainstream advancement of manufacturing technologies such as laser cutting and 3D printing will create new applications for the mechanism. (Sengupta & Bhatia, 2017).

Punde et al. 2020 carries out linkage analysis of the Jansen mechanism to construct a motorised robot locomotion prototype, assembled with fasteners. The paper identifies challenges faced during construction, such as rotation stiffness between the links, linkage bending, and lateral stability. It proposes design solutions to resolve these challenges (Punde et al., 2020).

There are also multiple project examples online which adapt the Theo Jansen mechanism for robotic applications, but many projects draw incorrect conclusions about walking smoothness and stability due to poor literature study, with incorrectly implemented link ratios, incorrect leg pair and phasing, and poor assembly methods which increase rotation resistance. While there are many projects which motorise the system, there are few which harness natural wind energy for drive like the original Strandbeest.

No papers have been identified combining all these factors to create a design concept for planetary exploration in omnidirectional winds, making this a new field of study.

## **2.4 Planetary Environment of Titan**

While the aim of the project is primarily to develop an early locomotion design concept for a wind-powered explorer robot, the Titan environment has been considered as one of the test scenarios.

This robot design concept is applicable to all planetary terrains with an atmosphere, wind, and firm surface terrain. It is desirable that the atmosphere is

dense for the mechanism to work effectively. Besides Earth, the 3 main candidates in the solar system identified with a windy atmosphere and firm surface terrain to explore are Venus, Mars, and Titan.

Venus has a very dense atmosphere, but was immediately ruled out because of its extreme temperatures, atmospheric pressures, and sulphuric acid rain weather cycles. Considering the hostility of the environment, it can be assumed that any robot technology deployed here would disintegrate within minutes, regardless of its design for resilience. Mars also has a firm terrain for the mechanism to explore, as well as reasonable windspeeds, however does not possess an atmosphere dense enough to generate meaningful dynamic pressure to operate a sail or turbine wind energy capture mechanism to mechanically power locomotion. (Taylor et al., 2018) (Banfield et al., 2020).

Titan was selected as the most feasible environment for this system to operate due to its current scientific interest, firm terrain, and dense atmosphere which is not lethal like Venus, but produces a usable dynamic pressure for a wind energy capture mechanism unlike Mars. The environment there is cold, but survivable if the appropriate materials are used in a real mission scenario. (Lorenz, 2017) (Landis & Oleson, 2021).

Table 1 below compares surface level environment data gathered from the Huygens probe and other studies, compared to Earth's environment:

**Table 1 Environment conditions of Earth and Titan**

| Parameter           | Earth                                       | Titan                                            |
|---------------------|---------------------------------------------|--------------------------------------------------|
| Surface Pressure    | 1013 mbar<br>(SKYbrary, 2020)               | 1470 mbar<br>(NASA, 2018)                        |
| Atmospheric Density | 1.225 kgm <sup>-3</sup><br>(SKYbrary, 2020) | 5.3 kgm <sup>-3</sup><br>(Landis & Oleson, 2021) |

| Parameter                    | Earth                                                             | Titan                                                                                                     |
|------------------------------|-------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Surface Wind Speed           | 3.3 ms <sup>-1</sup> average / typical<br>(Climate Signals, 2018) | <1 ms <sup>-1</sup> average / typical<br>(Lorenz, 2017)                                                   |
| Gravitational Field Strength | 9.81 ms <sup>-2</sup>                                             | 1.352 ms <sup>-2</sup><br><br>(Johns Hopkins University Applied Physics Laboratory, 2025)                 |
| Solar Irradiance             | 1361 W/m <sup>2</sup><br>(ARKA, 2025)                             | 15.2 W/m <sup>2</sup><br>(Lil et al., 2011)                                                               |
| Surface Terrain              | Varied: oceans, deserts, forests, grasslands                      | Frozen plains, dunes, lakes of methane<br><br>(Johns Hopkins University Applied Physics Laboratory, 2025) |

As shown from the table above, Titan has a 45% higher ambient atmospheric pressure than Earth, but has a significantly higher atmospheric density, around 440% denser than Earth's. As a result, despite its lower typical windspeed, even a light breeze can be used to generate usable dynamic pressure to operate a wind energy capture mechanism to drive robot locomotion. The weak solar irradiance on Titan proves the infeasibility of solar cells for power generation, meaning RTGs are the only existing option if natural sources such as wind are not utilised, which is extremely expensive.

Terrain will also be a consideration during the prototype test scenario. Titan's frozen, sandy plain can be simulated using a rough, firm surface. It also has a very low gravitational field strength at just 14% of Earth's, which can be simulated in the lab with weight offset methods.

The most dynamic pressure of a typical gust can be calculated using:

$$q = \frac{1}{2} \times \rho \times v^2 \text{ (Swan, 2008)}$$

Where  $q$  is the dynamic pressure (Pa),  $\rho$  is the air density ( $\text{kgm}^{-3}$ ), and  $v$  is the windspeed ( $\text{ms}^{-1}$ )

Data from the Huygens probe shows that on the surface, the maximum typical windspeed is  $1 \text{ ms}^{-1}$  (Lorenz, 2017). Using the atmospheric density on Titan's surface, the maximum typical dynamic pressure exerted on the robot and its wind energy capture system can be calculated:

$$\rho = 5.43 \text{ kgm}^{-3}, v = 1 \text{ ms}^{-1}$$

$$q = \frac{1}{2} \times 5.43 \times 1^2 = 2.715 \text{ Pa}$$

Simulating this using Earth's sea level atmospheric density, the required windspeed to achieve this dynamic pressure can be calculated:

$$q = 2.715 \text{ Pa}, \rho = 1.225 \text{ kgm}^{-3}$$

$$v = \sqrt{\frac{2*q}{\rho}} = \sqrt{\frac{2*2.715}{1.225}} = 2.105 \text{ ms}^{-1}$$

Compared to typical Earth windspeeds shown in Table 1,  $2.105 \text{ ms}^{-1}$  is a low windspeed for Earth conditions; it is a very gentle breeze.

## 2.5 Knowledge Gap and Problem Statement

From the aforementioned points, it is evident that while Titan is a desirable environment to explore, the low surface solar irradiance for solar cells makes RTGs the only existing viable power source for locomotion, as is the case for the Dragonfly mission. Its inherent power decay model and battery degradation means that peak power and locomotion power budget is only produced at the start of the mission, subsequently declining over the following years as other mission systems become prioritised. This limits the range extension of the robot from the landing site year on year, missing out on potentially valuable scientific findings. Previous missions show that electrically powered locomotion systems are expensive and require large storage space to transport. Once landed, a

perfect locomotion deployment is critical for nominal mission continuation. (The Planetary Society, 2020) (NASA, 2020) (Schmitz, 2020).

Addressing these issues will require the development of a low-cost integrated locomotion system, demanding minimal electrical power to operate, and requiring minimal storage for transportation. The system needs to be robust for the hostile environment, be easy to manufacture and assemble, as well as being easy to maintain.

## **2.6 Thesis Contribution**

The contribution of this thesis will be to propose and investigate the feasibility of an early low-cost, low-power, mechanical planetary robot locomotion design concept for applications such as Titan exploration, which will minimise storage requirement for transportation by being fabricated on site.

Its simple mechanical Jansen-inspired linkage solution will allow low-cost manufacture and assembly, while increasing the robustness and resilience of the robot against harsh planetary conditions. By developing prototypes which will be 3D printed and assembled together, it will inherently be designed with ISRU additive manufacturing processes in mind; all of its mechanical components will have base-heavy features. Simple connecting interfaces between components will allow ease of assembly, maintenance and repair. The low-power demand will be achieved by allowing the system to be powered directly by natural wind energy, which requires a mechanism that can convert omnidirectional wind gusts to linear forward robot motion. This will completely offset power demand of the system, allowing it to function independent to the electrical power generation system.

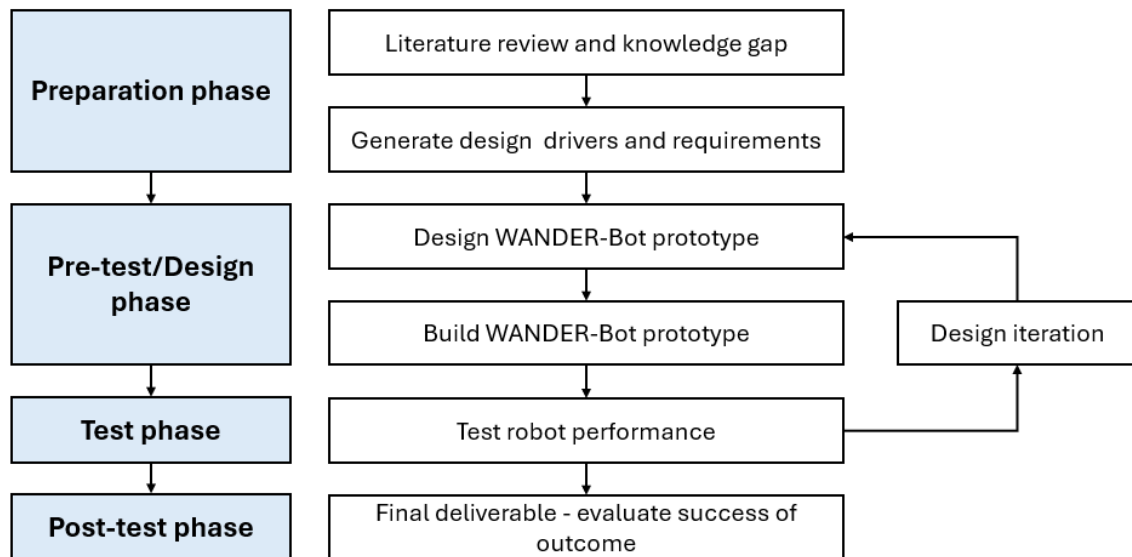
This will be the first paper to propose, develop, and carry out experimental performance testing of a natural omnidirectional wind powered Jansen mechanism walking robot, designed for future ISRU operations, for future planetary applications such as Titan.

### 3 Methodology

This chapter covers how the Thesis will be structured to meet the aforementioned aim, objectives, and requirements, to ensure that they are satisfied systematically.

This project will be divided into 4 main phases: Preparation phase, Pre-test/Design phase, Testing phase, and Post-Test phase.

The following flowchart Figure 3-1 shows the chronology and workflow of the Thesis project:



**Figure 3-1 Project workflow and methodology**

As part of the Preparation phase, Chapter 2 Literature Review meets objectives 1a to 1f. It identifies the limitations of existing power generation systems for planetary robots, limitations of existing locomotion methods, future mission proposals using air as a medium for locomotion, or missions which plan to use the Jansen mechanism. It also covers the development, optimisation, and existing applications of the Jansen mechanism and Strandbeest design, looking at its respective link ratios, and features to ensure optimum stability. The environmental conditions of Titan are also investigated, to evaluate which of these conditions can reasonably be replicated on Earth, given the project

constraints. From the research, the chapter concludes by identifying the current knowledge gap, and contribution of the project.

Chapter 4 meets objective 2 by generating design drivers and requirements for the WANDER-Bot design. This chapter will also identify project constraints which need to be considered during, design, development, and testing.

Entering the Design Phase, chapter 5 meets objective 3 by covering the evolution of the integrated robot system concept design. The walk-through of the design evolution of the robot system includes simulation, design, and manufacture of prototype iterations. Creating the final prototype requires development of motion simulations to study the walking gait of the mechanism to ensure stable foot-ground contact, and development of the Jansen-locomotion assembly. The development of a gearing mechanism ensures sufficient torque multiplication is supplied to rotate the mechanism. Alongside this, a wind energy capture mechanism is developed to maximise efficiency and provide the most mechanical work for the system in the given windspeed, direction, and weight scenarios. The design of each prototype iteration will be informed by the success and limitations of previous prototypes in experimental testing.

For the Test Phase, chapter 6 meets objective 4 by carrying out an experimental testing campaign of the walking mechanism, wind capture mechanism, and integrated system. For the Jansen mechanism, tests will record the walking gait of the foot, comparing the traced shape of the prototype to the generated profile of the foot in the motion simulation. Key parameters such as step length, step height, and qualitative analysis of the general shape can be compared to the simulation to verify the accuracy of the system in reproducing the optimal stability profile. For the locomotion assembly, cycling tests can be run to assess smoothness of the mechanical torque delivery for each cycle, identifying areas of the cycle where the rotation resistance increases. To measure efficiency of the wind energy capture mechanism, performance characteristics such as RPM at different windspeeds can be measured to quantitatively analyse performance improvements with each design iteration. As for the integrated system, experimental tests can be used to record the self-start and walking capability of

the robot in different wind conditions with its full weight, and with weight offloading. The results gathered from these experiments will inform design changes in the subsequent design iterations. The discussion section in this chapter will conclude by identifying the successes and limitations of the experiments carried out, to propose future changes for more accurate and representative data collection.

As part of the Post-test Phase, chapter 7 will conclude by evaluating the success of the project in achieving the aforementioned objectives. It will analyse the success of the robot design concept in achieving the project aim of having simple mechanical linkages in the locomotion mechanism, driven directly by wind power, able to walk forward regardless of wind direction, at low wind speeds. The section will conclude with future work which will propose further considerations to mature the robot design, to make it more capable for planetary exploration.

## **4 Project Design Drivers, Requirements, and Constraints**

With the goal of meeting objective 2, these following design drivers, requirements, and project constraints have been generated for the robot system design, based on the identified knowledge gap, thesis contribution, aim, and objectives.

The design drivers for the robot are as follows:

### **4.1.1 Robot Design Drivers**

1. Low-cost design and assembly.
2. Robust construction which is easily maintainable for operation in hostile environments.
3. Minimised storage space for transportation.
4. Stable walking gait.
5. Minimised power demand to operate.

From these, the following requirements have been generated:

### **4.1.2 Robot Design Requirements**

1. The robot shall use simple Jansen-inspired linkages for its legged locomotion.
2. The robot locomotion solution shall be purely mechanically driven.
3. The robot locomotion shall be powered purely by wind energy.
4. The robot shall be able to walk forward in omnidirectional wind conditions.
5. The robot locomotion shall provide smooth and stable forward motion.
6. The robot assembly joints shall be shielded to prevent dust ingress.
7. The robot locomotion components shall be fabricated using additive manufacturing methods, such as 3D printing.
8. The robot shall be able to walk in 14% weight offset conditions simulating Titan gravity.
9. The robot shall use simple interfaces between connecting components.
10. Testing of the integrated robot locomotion system shall be conducted on firm rough terrain simulating Titan's frozen plains.

#### **4.1.3 Project Constraints**

1. The robot system design concept prototypes shall be manufactured using 3D printing.
2. The project shall be completed within the allocated time and cost budgets.
3. Procured components and tools for the robot manufacturing and testing shall be low cost and widely available.
4. Robot testing shall take place in Cranfield Space Lab 2, where reasonable environmental conditions of Titan within project budgets will be simulated, such as wind conditions, terrain, and weight.

## 5 Robot Concept Design and Prototype Development

This chapter aims to satisfy objective 3, discussing the design evolution of the integrated robot system in accordance with the generated design requirements in chapter 4. It will walk through the parallel development of the 3 main constituent parts of the integrated system in each iterative prototype, which includes the Jansen leg locomotion mechanism, gearing mechanism, and wind energy capture mechanism.

### 5.1 Motion Simulation of the Jansen Mechanism Leg

The aim of this exercise was to assess the walking gait of the Jansen mechanism leg, with the link ratios available in literature. This included studying the shape profile of the foot, to verify literature. It also allowed pre-emptive identification of potential collisions between the links during each cycle, mitigatable with link design changes. Motiongen.io was the software used for motion simulation, seen in Figure 5-1. Links were inserted, sized, and connected together at their pivot points to constrain them to their single DoF. Their lengths were determined by the ratios found from literature. With the rotation point defined on the crankshaft, the simulation was set to run, tracing out the shape drawn by the foot node of the mechanism. A video of the running simulation can be found by following the link in Appendix B Further Robot Videos and Pictures.

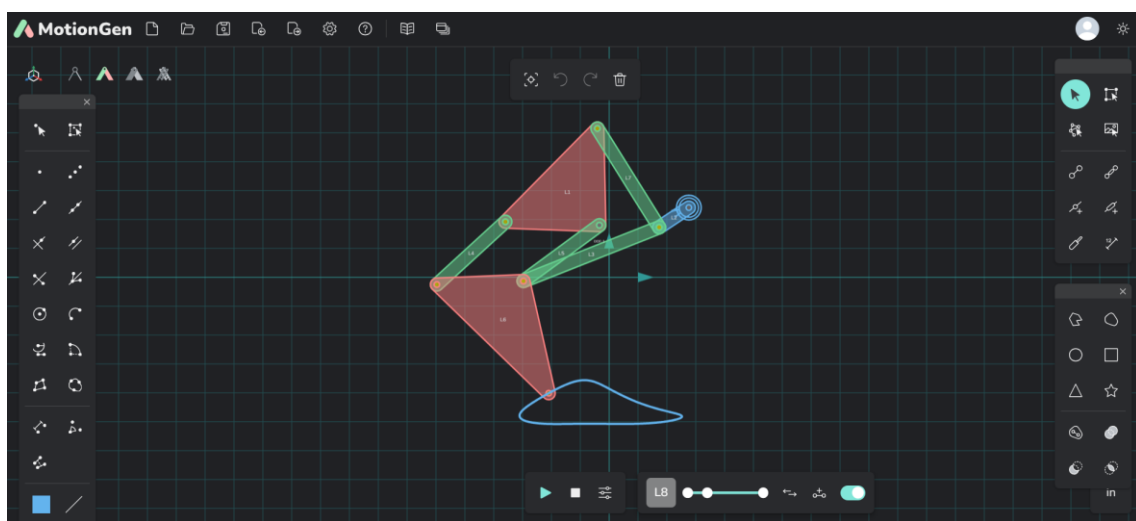


Figure 5-1 Motion simulation of Jansen mechanism on Motiongen.io

Comparing the profile drawn from the simulation with literature from Patnaik & Umanand, 2016, the general profile shape matched, as well as the step length. However, there was a 17% reduction in what was expected from the step height, but was deemed acceptable, as a less pronounced peak height and thinner profile meant less extreme angles were created by the links, making the cycles smoother. This simulation was later used to verify the experimental prototype walking gait, where the experimental result accurately reproduced the results expected from the simulation (see Experimental Analysis of the Foot Profile section).

From the motion simulation cycles using straight links, a potential collision was identified between link K and pivot BCD when the foot reaches the peak. This informed a curved design change on link K before the first prototype was built, for collision mitigation.

## 5.2 Robot Design Evolution

Table 2 summarises the main aims, successes, and required future improvements for the prototypes developed in this project:

**Table 2 WANDER-Bot prototypes summary**

| <b>Prototype Model</b> | <b>Aim</b>                                                                                                    | <b>Successes and future improvements</b>                                                                                                                                                                                                                                 |
|------------------------|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| WANDER-Bot 1.0         | Small scale prototype to experimentally test Jansen link ratios and prove feasibility of linkage manufacture. | Mechanism found to be feasible to manufacture with 3D printing. Press-fit bearing installation was a success. Largely smooth cycling motion which followed the Jansen walking gait. More work required to reduce friction between the links and eliminate need for glue. |

| <b>Prototype Model</b> | <b>Aim</b>                                                                                                                                  | <b>Successes and future improvements</b>                                                                                                                                                                                                                                                                                                       |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| WANDER-Bot 1.5         | Make iterative improvements on previous design to improve smoothness and make assembly fully press-fit for ease of prototype manufacturing. | Support material eliminated entirely, full assembly became interference fit, no longer requiring glue for assembly. Introduced washers which removed friction between links and smoothened rotation further. Next step: upscale model for clarity of detailed features to match printer resolution and create full Jansen locomotion assembly. |
| WANDER-Bot 2.0         | Create full upscaled Jansen mechanism assembly and use as testbed platform to develop turbine and gearing mechanisms.                       | Larger design features were easier to replicate for the printer resolution, allowing for more solid interference fits. Heavy weight of links caused rotation resistance due to the mechanical level arm load on the crankshaft when lifting the leg, causing some 'blocky' movement.                                                           |

| <b>Prototype Model</b> | <b>Aim</b>                                                                                                                                | <b>Successes and future improvements</b>                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| WANDER-Bot 2.5         | Address the weight issue of previous link design to reduce and spread out the torque spikes needed to rotate the mechanism.               | Link lightening campaign was a success. It reduced production time, and the torque spikes needed to rotate the mechanism. Full assembly walked forward smoothly with low resistance. Lateral stability improved with frame stiffening. Successfully used as a platform to develop turbine and gearing systems. In the end, the system was able to self-start in omnidirectional winds, but reliably only at higher windspeeds. Aim met, but further refinement desirable. |
| WANDER-Bot 3.0         | Optimise the robot design to make it capable for the desired lower windspeed omnidirectional start-up. Refine gearing and turbine design. | Reduction gearing doubled from 8:1 to 16:1 ratio for improved torque. Turbine developed, balancing print quality with blade feature optimisation, for increased mechanical work output. Additional work required to strengthen gearing rotation shaft assembly to prevent gear slip, and improve turbine concentricity mounting to stop precession in high-speed winds.                                                                                                   |

| <b>Prototype Model</b> | <b>Aim</b>                                                                                 | <b>Successes and future improvements</b>                                                                                                                                                                                    |
|------------------------|--------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| WANDER-Bot 3.5         | Reduced joints and connections in gearing and turbine shaft assembly to improve stability. | Final prototype able to self-start in omnidirectional winds, at moderately low windspeeds. Aim, objectives, and requirements of project and design successfully met. Future work: mature design further for robot autonomy. |

The remainder of this chapter covers the details of the development process in more depth.

In order to satisfy requirement 7, the general philosophy of this design is that all main components should be 3D printable to make them ISRU compatible, using additive 3D printing manufacturing, with base-heavy, ground-up-build design features. In later designs, this is further improved, with newer iterations also requiring no 3D printed support material to build. Newer prototypes also removed the need for adhesives, being designed to be easily repairable if any components needed replacement during testing and development. For ease of iteration and upgrades, all components in these prototypes have been designed to be interference fit, relying purely on tight tolerances and friction to hold the assembly together. While this is effective for prototyping, a more mature prototype would have fastened joints.

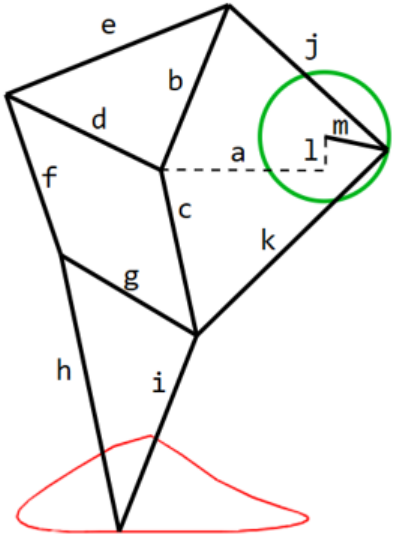
### **5.2.1 WANDER-Bot 1 design and development**

The first prototype 1.0 was a scaled down model of a single leg assembly. Designed to test the Jansen link ratios in literature and ensure smooth movement, it was also manufactured to assess the feasibility of manufacturing the mechanism using 3D printing, and assess ease of assembly.

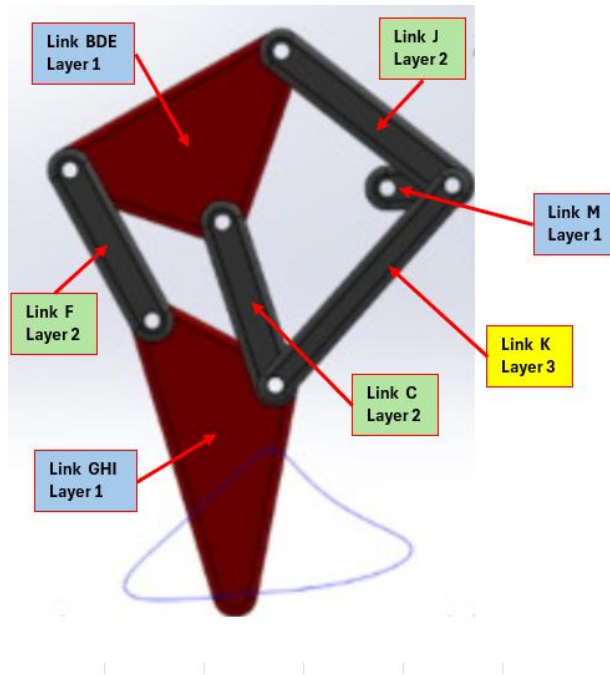
### 5.2.1.1 WANDER-Bot 1.0 Prototype

All structural components in this robot and mechanism were constructed using PLA material. Using 1 mm as the base unit for the linkage assembly, the dimensions of the links between the pivot points are shown in Table 3:

**Table 3 WANDER-Bot 1 prototype Jansen link dimensions**

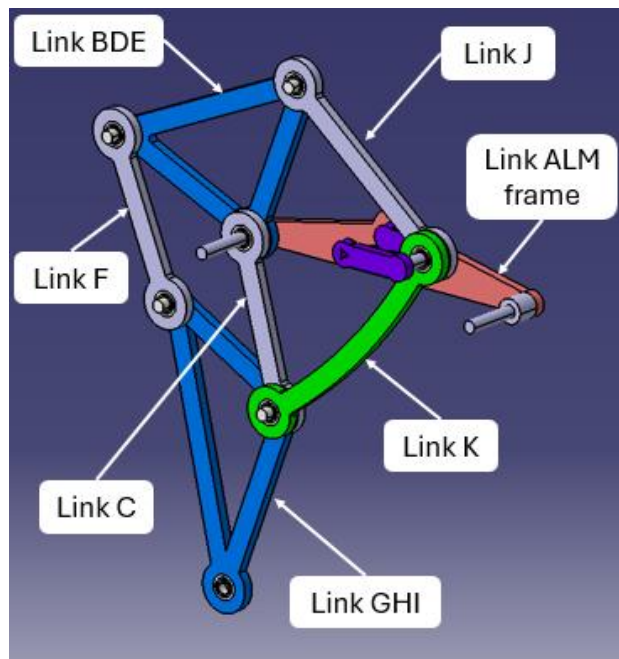
| Link element | Length (mm) |  |
|--------------|-------------|-------------------------------------------------------------------------------------|
| A            | 38.0        |                                                                                     |
| B            | 41.5        |                                                                                     |
| C            | 39.3        |                                                                                     |
| D            | 40.1        |                                                                                     |
| E            | 55.8        |                                                                                     |
| F            | 39.4        |                                                                                     |
| G            | 36.7        |                                                                                     |
| H            | 65.7        |                                                                                     |
| I            | 49.0        |                                                                                     |
| J            | 50.0        |                                                                                     |
| K            | 61.9        |                                                                                     |
| L            | 7.8         |                                                                                     |
| M            | 15.0        |                                                                                     |

In order to prevent structural collision between the links, careful thought had to be put into how the links would be layered on top of each other, while keeping the structure as compact as possible to not compromise lateral stability. The layering of the links is shown in Figure 5-2:



**Figure 5-2 Jansen linkage layering**

Based on the dimensions and layered design discussed above, the following design was modelled on CATIA V5:



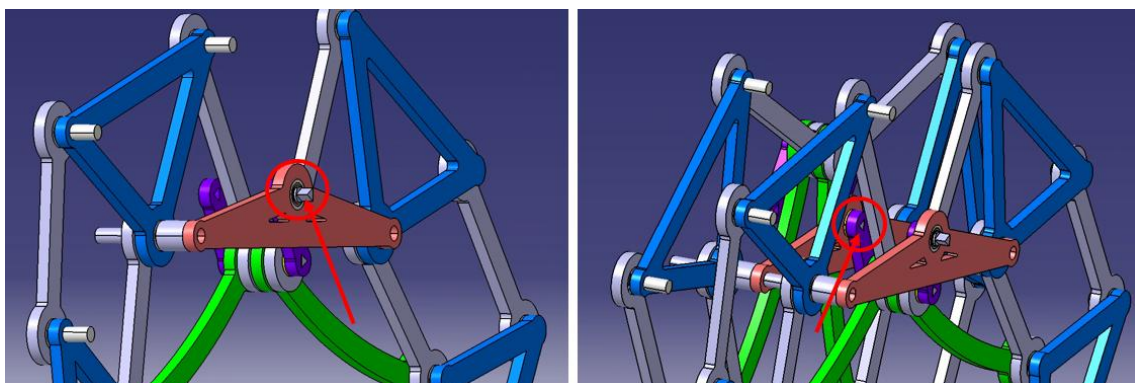
**Figure 5-3 WANDER-Bot 1.0 CAD model**

In order to minimise resistance between the joints, it was decided that housed bearings would be used to smoothen the motion. For the given size of this

assembly, housed bearings with 3 x 6 x 2.5 mm inner diameter, outer diameter, and thickness was used. Double shielded bearings were selected to prevent ingress such as dust, sand, and fluids from compromising rotation smoothness of the bearings. This helped the design to meet requirement 6, which stated that joints should be shielded from dust ingress to improve design robustness.

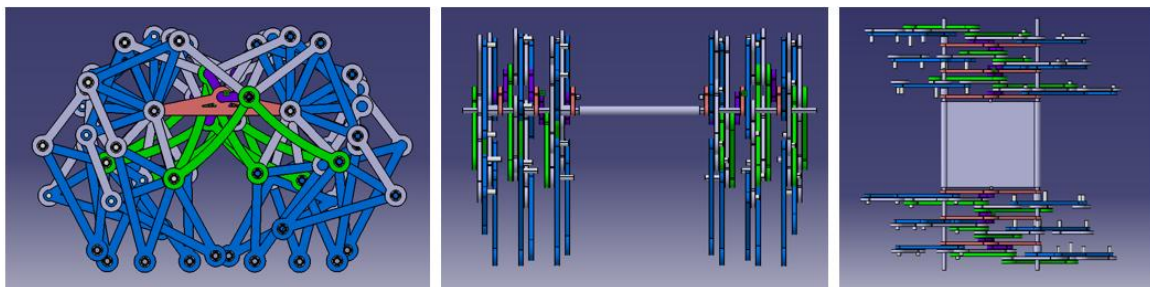
The 3D printed shafts on which the bearings would rotate were 3 mm in diameter. Due to the motion simulation, the design of link K was changed to a curve instead of a straight bar, anticipating a potential collision with the BCD shaft. 0.5 mm stand-offs were introduced into the link design as a means of maintaining a separation between overlapping links to reduce friction between their faces. Links such as BDE, GHI, and ALM were joined together as single components to ease manufacturing and assembly. In order to keep the structure light, and infill of 15% was used, which was sufficient to maintain some structural rigidity for light loads.

Considering future leg assemblies, a rotating crankshaft mechanism, similar in design to the crankshaft of an internal combustion engine, was developed to hold the centre of the legs in place while preventing collisions between the rotary shaft and moving legs. To minimise assembly time, the 120° phasing offset between the legs was achieved through design instead of measurement. The end of each leg pivot shaft featured an equilateral triangle extrusion, which could engage, with an interference fit, into the triangular slot of the next leg pivot arm at 120° offset rotation, as shown in Figure 5-4:



**Figure 5-4 Triangular extrusion and engagement for 120° phase offset**

All components were standardised in the design to allow easier leg assembly; it vastly reduced the amount of unique component parts. By doing this, it meant that a given link design could be used in multiple locations across different legs, eliminating the need for additional time and effort into ensuring that each unique leg is assembled correctly. End caps were designed to be glued to the end of the anchor shaft to further shield the bearings from dust and prevent the link pieces from sliding off the rods. Figure 5-5 below shows what a fully assembled Jasen locomotion would have looked like, if the prototype 1 design was used for the full assembly. Creating the full model was necessary to better understand how parts from a single leg and leg pair module engage with others.



**Figure 5-5 Fully locomotion assembly model for WANDER-Bot prototype 1**

After the first single leg prototype was completed, rotation tests were conducted to assess its success in recreating the walking gait and smoothness required. It was found that the optimal walking gait of the robot was successfully achieved, with the ground contact point on the leg tracing the desired tear-drop-type mound shape with a flat bottom, and long ground contact time. The press-fit installation of the bearings was a success; they offered the expected smoothness to the mechanism, but it was observed that there was some ‘blocky’ movement in the leg as it went through each cycle, due to spikes in resistance at certain points of the rotation. This was addressed and reduced significantly later through refinement of the structure in the second iteration of the prototype. Provisions were made at the bottoms of the legs to install bearings for potential future foot designs.

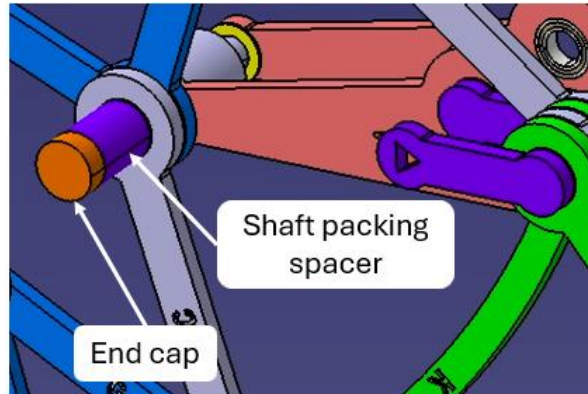
It was also found that the 0.5 mm stand-off features on the 3D printed links were ineffective, as they were beyond the resolution of the 3D printer to reliably

recreate. As a result, it resulted in friction between link component faces which caused additional friction. As the ALM frame was a standardised component designed for engagement with other frames and leg assemblies, doing a single leg construction meant that there was lateral movement between the link pivots and shaft, meaning the links were no longer constrained in a way that only gave them 1 degree of rotational freedom only. This additional sliding movement and link misalignment caused considerable resistance while the mechanism cycled through each rotation. While in a full assembly this gap would be filled with other link pieces, they needed to be packed for the second iteration of the prototype to eliminate movement. Gluing end caps was also an issue; the tight-fit nature of the assembly meant that excess adhesive from the end caps trickled down the frame shaft into the bearings, increasing their rotational resistance.

The initial design of the ALM frame had overhangs which required support material to build. This increased manufacturing time for the component, increased material consumption, and increased assembly time as the support material had to be removed manually before it could be used.

#### **5.2.1.2 WANDER-Bot 1.5 Prototype**

The second prototype iteration brought several design changes to address much of the limitations faced by WANDER-Bot 1.0. The new ALM frame was redesigned to eliminate support material, reducing material consumption and speeding up the manufacturing process. The poorly functioning stand-off features on the links were removed entirely, and instead replaced with M3 3 x 6 x 0.5 mm washers which stood as the spacers between the links. This was a vast improvement over the previous design in reducing friction between the link faces. In order to remove lateral movement of the links along the shafts, hollow spacers were 3D printed to pack the length of the shaft and ensure that the links were held in a more compact way to reduce their sliding movement. The end caps which were initially glued were now redesigned to be interference fit only, meaning glue was no longer required for the assembly of the mechanism. Both changes can be seen in Figure 5-6:



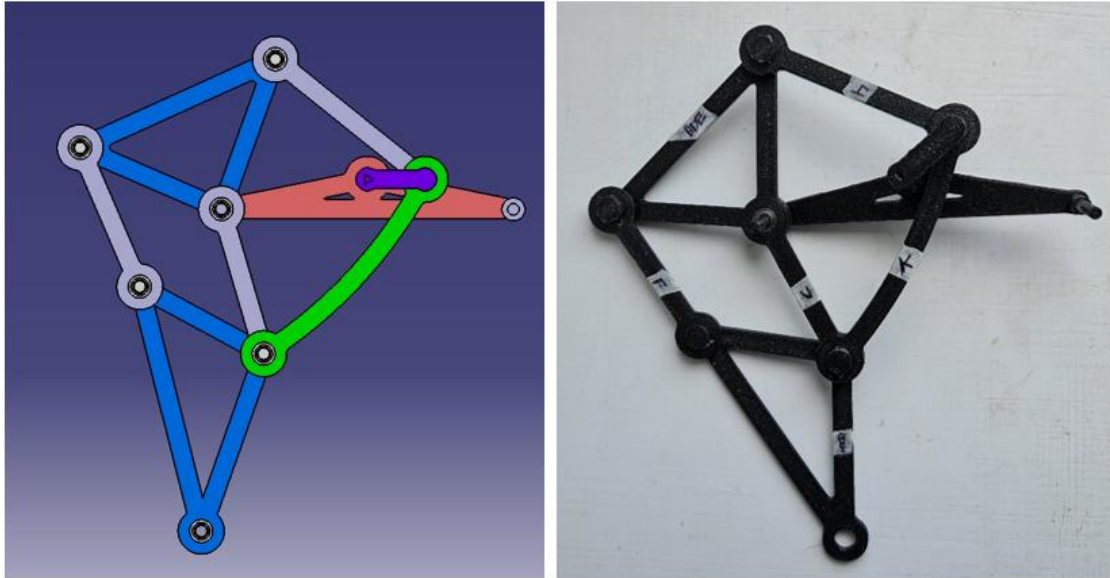
**Figure 5-6 WANDER-Bot 1.5 spacers and end caps**

Another benefit of this is that the caps could be removed more easily to remove and slide out the links to replace them if needed, making the construction of the leg system easier to repair and maintain, in order to meet requirement 9 and easy maintenance design driver.

Combined, all these changes also contributed to removing most of the ‘blocky’ movement of the leg rotation cycles seen in the first prototype. The motion became very smooth, with minimal resistance. It was evaluated that in a full locomotion assembly, this mechanism could tangibly be rotated using wind power only, if an effective turbine and gearing mechanism was developed, featuring a reduction gearbox for torque amplification.

Some limitations were still observed with this design: small features such as the triangle extrusion on the 3 mm crankshaft to allow the 120° rotation offset could not be reliably replicated every time by the 3D printer. It was concluded that this was due to limitations with printing resolution with the small scale of this prototype, and not an inherent design flaw. Upscaling this design in future prototypes would enable the printer resolution limitation to diminish.

The CAD model and working prototype of WANDER-Bot 1.5 can be seen in Figure 5-7. A video comparison of WANDER-Bot 1.0 and 1.5 can be found by following the link in Appendix B Further Robot Videos and Pictures.



**Figure 5-7 CAD model and final working prototype of WANDER-Bot 1.5**

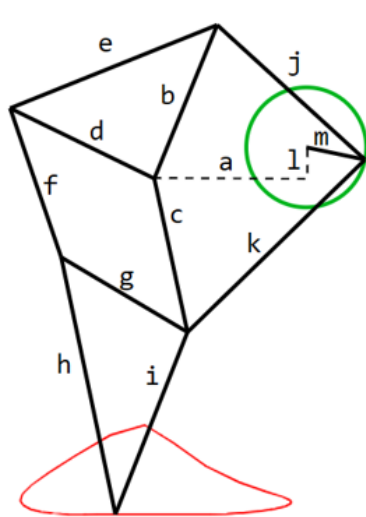
### **5.2.2 WANDER-Bot 2 design and development**

The purpose of prototype 2 was to upscale the designs of the components used in prototype 1 and see how well they can be joined together in a full Jansen mechanism assembly. Increasing scaling makes the prototype easier to construct without requiring high levels of hand dexterity, and larger feature sizes are easier to 3D print to reasonable levels of accuracy. This prototype was designed to be used as the testbed to design and develop the turbine and integrated gearing mechanism, allowing the assembled robot to walk forward in all wind directions.

#### **5.2.2.1 WANDER-Bot 2.0 Prototype**

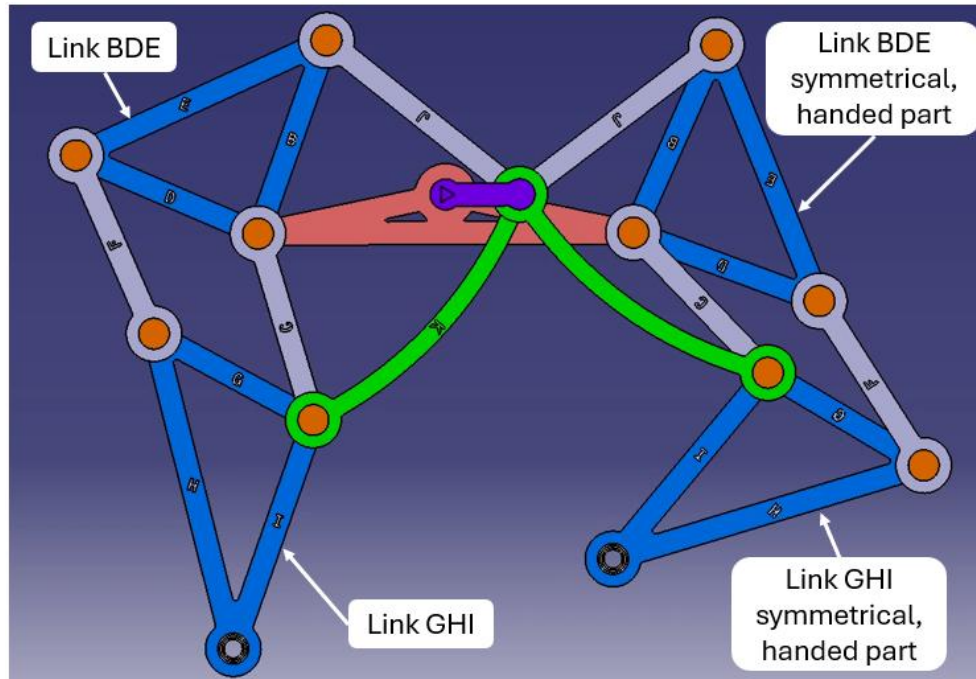
Now 60% larger in total size than WANDER-Bot 1.5, this new design used a 1.6 mm base unit for the Jansen linkage, and its specific link dimensions are listed below in Table 4:

**Table 4 WANDER-Bot 2 prototype Jansen link dimensions**

| Link element | Length (mm) |  |
|--------------|-------------|------------------------------------------------------------------------------------|
| A            | 60.8        |                                                                                    |
| B            | 66.4        |                                                                                    |
| C            | 62.9        |                                                                                    |
| D            | 64.2        |                                                                                    |
| E            | 89.3        |                                                                                    |
| F            | 63.0        |                                                                                    |
| G            | 58.7        |                                                                                    |
| H            | 105.1       |                                                                                    |
| I            | 78.4        |                                                                                    |
| J            | 80.0        |                                                                                    |
| K            | 99.0        |                                                                                    |
| L            | 12.5        |                                                                                    |
| M            | 24.0        |                                                                                    |

This version featured rotation shafts which were now twice the size of the previous design, at 6 mm diameter. Thus, the bearings used were also larger: 6 x 10 x 3 mm. The larger shaft diameter ends allowed the triangular slot and pin designs for the crankshaft assembly to be easily reproduced by the 3D printer, easing the assembly process and 120° offset. As the physical links have to be thicker to accommodate the new press-fit bearings, they had to undergo some design changes.

To start the robot assembly, first one pair of Jansen legs was 3D printed and assembled to the ALM frame. Most of the links were made with rotational symmetry in consideration, but handed parts had to be made for links BDE and GHI due to the nature of their design for installation on the symmetrical leg, as seen in Figure 5-8:



**Figure 5-8 WANDER-Bot 2.0 CAD Jansen leg pair module CAD model**

The correct sizing of this prototype mean that all the links needed for a Jansen leg pair could be printed on a single build plate with the optimal placement generated by the software. It was noted that one of the limitations during the assembly of WANDER-Bot 1.0 was that some links were extremely similar in size, namely C and F, which only differ in size by 0.1 mm between their pivot points (see Table 3), making them visually indistinguishable. As the Jansen mechanism walking gait is sensitive to small changes in link ratios, additional time had to be spend measuring the links with digital callipers to ensure they were installed correctly. This slowed assembly time, and it was noted that a future iteration would need marking to allow them to be installed faster. Prototype 2 achieved this by having the link letters imprinted on the side, as shown in Figure 5-8, which significantly improved assembly speed.

The larger assembly features in the design increased the contact area between the joins, making the press-fit installation more solid. Once fully assembled, the Jansen leg pair rotated smoothly on the frame, with the bearings, washers, crankshaft, and leg link mechanism design working as intended. The walking gait of the mechanism was tested experimentally and verified against the simulation.

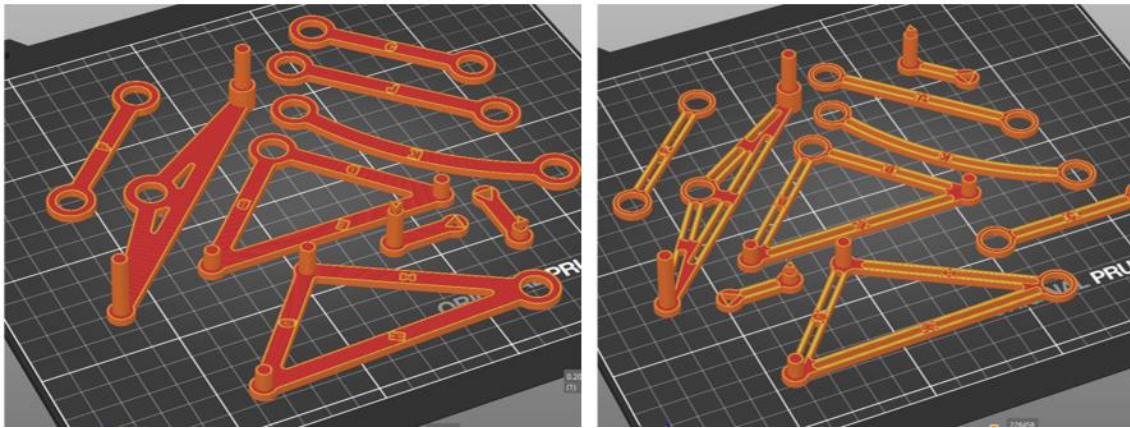
For this, a pen was concentrically held in place using the hole provisions for future feet design, and used to trace the foot movement profile shape on a plain background. For more details, see Experimental Analysis of the Foot Profile section. The walking gait successfully showed that the shape accurately traced the optimal Jansen mechanism gait.

However, upon testing and cycling the leg pair module, it was found that there were momentary spikes in resistance, where more torque was required to rotate the mechanism. One of these moments appeared particularly where the links in the leg were collapsing into its most compact shape in the cycle, with sharp acute angles between the link joints, causing some rotation resistance. Another main point in the cycle is when the weight of the full leg had to be lifted off the ground. Despite the general smoothness of the cycles, this brought back some of the 'blocky' movement behaviour of the leg. More details of these findings can be found in the Experimental Analysis of the Jansen Locomotion Mechanism Smoothness section. As it is desirable that the torque should be smoothed evenly across each cycle for the turbine and gearing mechanism to be effective, efforts had to be made where possible to address these concerns.

The first issue was challenging to resolve, as it was inherent to the natural walking gait of the mechanism and the link movement; it would have to be investigated in further research. However, the second issue of weight could be more easily resolved by lightening the link structure design, while ensuring sufficient structural rigidity and integrity to support the weight of the robot mechanisms and hold the interference fit components in place. As part of the lightening campaign, the width of each link bar was reduced from 7.5 mm to 6 mm, the outer diameter of the hole accommodating the bearings was reduced from 14 mm to 10 mm. New lightening slots were introduced throughout the structure. Another option was to reduce the PLA 3D printed material infill, but this was avoided as it was decided that this would compromise the structural rigidity of the links, leading to flexing along the link bars when loads were applied, such as the weight of the turbine and gearing. A central connection bar was still included in the centre of each link between the slots which contained the letter imprint. These prevented flexing of the thin

material along the width of the structure. They also served as pick-up points when removing the stuck 3D printed links from the print bed, to prevent breakage of the thin walls.

The improvements brought by the lightened design resulted in a mass reduction from 27.63 g to 21.28 g for a single leg assembly, shown in Figure 5-9. With a reduction of 23%, this also meant that less material now had to be consumed for manufacturing. Likewise, the time taken to manufacture also decreased by 26%. In summary, the link design lightening campaign contributed to easing the assembly process, reducing material consumption, reducing mechanism weight, and reducing manufacturing time.

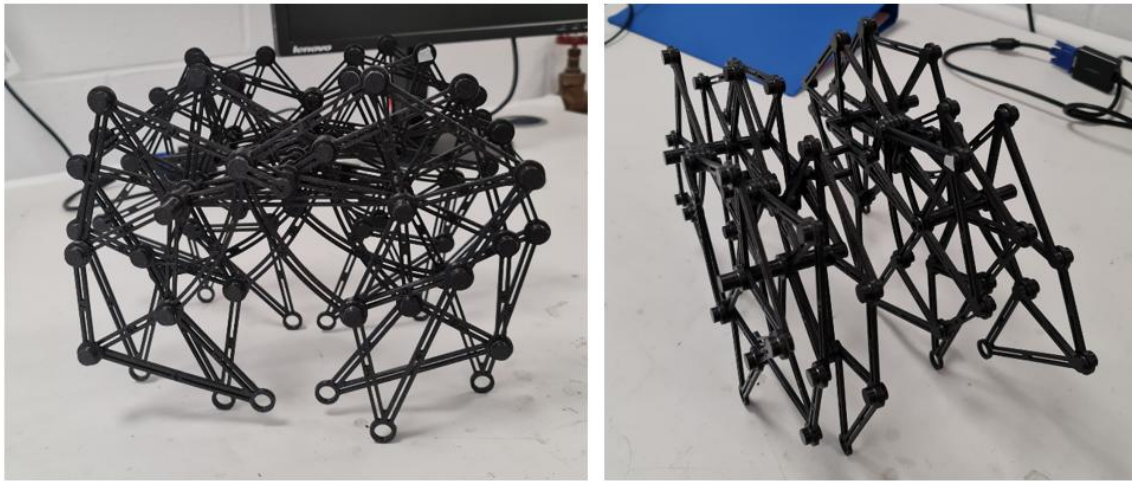


**Figure 5-9 WANDER-bot 2.0 vs 2.5 lightened link design on 3D printing software bed**

#### **5.2.2.2 WANDER-Bot 2.5 Prototype**

WANDER-Bot 2.5 utilised the new lightened link design. Firstly, a Jansen leg pair module was constructed again, and compared to the previous iteration. The new mechanism showed vast improvements in rotation smoothness, with much of the 'blocky' movement removed. As intended, the torque required to lift the leg off the ground in its cycle was notably less than WANDER-Bot 2.0. Satisfied with the outcome of the redesigned leg pair module, 5 more were assembled and connected together, with a temporary centre structure, to complete the legged locomotion part of the robot. The locomotion assembly mechanism can be seen in Figure 5-10. A video hyperlapse of the construction of the WANDER-Bot 2.5

Jansen locomotion mechanism can be found by following the link in Appendix B Further Robot Videos and Pictures.



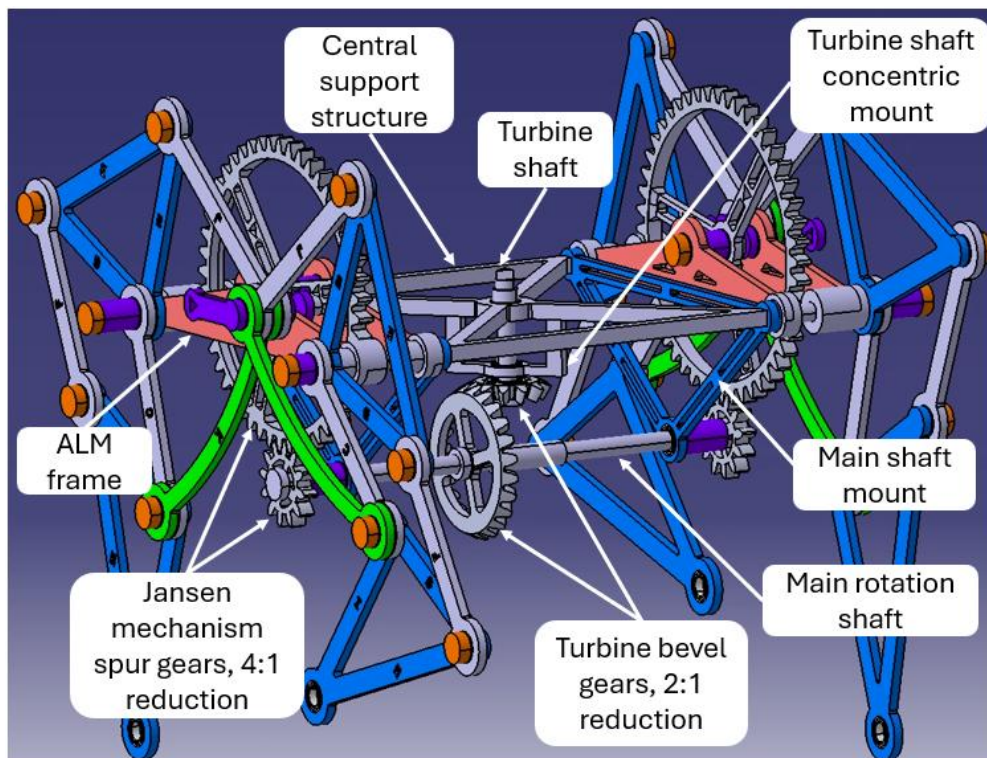
**Figure 5-10 WANDER-Bot 2.5 full locomotion assembly**

Preliminary testing showed that the robot was able to walk smoothly with a more uniform torque requirement. There were still some positions where the required torque to rotate the mechanism peaked, and these are analysed further in Experimental Analysis of the Jansen Locomotion Mechanism Smoothness section. A gentle push was able to slowly make the robot start walking forward, indicating that it was tangible to make this robot walk forward with the correct turbine and reduction gearing design. A video of the Jansen mechanism smoothness testing can be found by following the link in Appendix B Further Robot Videos and Pictures.

Satisfied with this outcome, the next step was to design the gearing mechanism and turbine. The gearing had to be designed in such a way that the clockwise rotation of the legs would be translated to a linear forward motion with both legged sides of the robot. Care also had to be taken to simplify the solution and minimise the number of gear engagements, to reduce friction as much as possible, so planetary gearing solutions were avoided.

For this, the general design was to have a bevel gear and pinion reduction, connecting to the turbine shaft and main rotation shaft. The bevel gears translated the vertical z axis rotation of the turbine to a horizontal x axis rotation for the main

shaft. Smaller spur pinions on the ends would rotate at the same speed as the main shaft. These engaged with a larger spur gear on the same plane, driving the Jansen mechanism assembly crankshaft on both sides with a notable gear speed reduction and increased torque. All of these 3D printed interconnecting shafts would be held in place and concentric with a series of bearing mount provisions from the main central structure. This structure itself was in turn mounted to the inboard ALM frames on the Jansen leg assembly. The architecture for this can be seen in Figure 5-11:



**Figure 5-11 WANDER-Bot 2.5 CAD model of integrated gearing mechanism on Jansen locomotion assembly**

Due to the press-fit nature of the whole assembly, it meant that there was a plethora of components, and a small amount of movement in each joint, translating to a noticeable lateral sway. This was most notable where the ALM frames interfaced with each other. Here, there was less engagement, as the slots were only 2 mm deep as opposed to the standardised 3 mm in other parts of the assembly. The initial nature of this design was to prevent support material from having to be used when it was being 3D printed. To rectify this, new adaptors

where 3D printed to fit to the ALM frames and shafts, which significantly increased the press-fit contact area between the frames, resulting in a more rigid assembly with significantly less lateral sway.

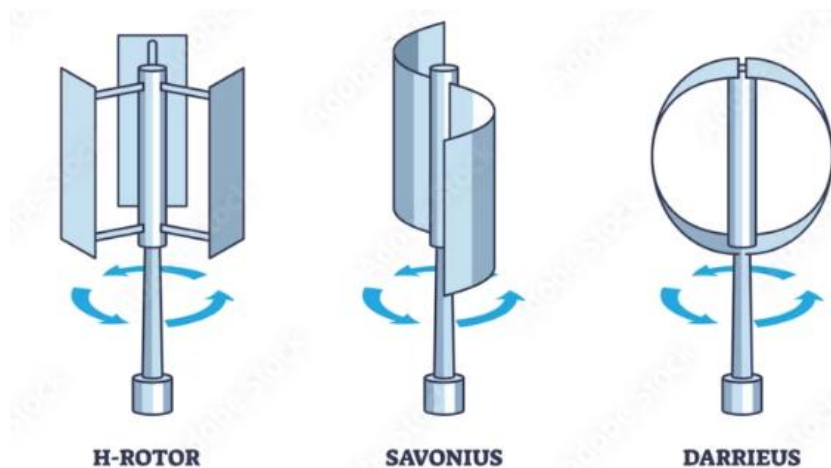
For the initial gearing mechanism, based on a rough idea of the force required to start moving the robot, it was decided that a gear reduction ratio of 8:1 would be sufficient to make the robot move forward, at least at higher windspeeds. The bevel gear engagement was set as 2:1 between the turbine shaft and main rotation shaft. Then, there was a 4:1 reduction between the main shaft the Jansen mechanism crankshaft. Together, this combination resulted in an 8:1 reduction ratio between the spinning turbine and the Jansen mechanism crankshaft. This integrated system directly correlates the 8x gear rotation speed reduction to an 8x increase in produced torque between the systems.

The next step was to generate the design solution for the wind energy capture mechanism. The original Strandbeest design used sails which could be unfurled over large areas to create the necessary force to move the system. However, this was quickly ruled out at the start of the project, as it prevented the robot system from achieving the requirement of being able to walk forward in all wind directions. Furthermore, a sail system would cause a 'dragging' effect, hauling the robot forward. This would cause the mechanism to cycle and take the next step, driven by friction at the foot. It is also an ineffective solution, as it inhibits the system from being able to achieve mechanical torque multiplication with a reduction gearbox. This limits capabilities such as being able to operate at lower windspeeds, or future control of torque, speed, and steering in the robot in matured future designs.

Using a turbine as a wind energy capture mechanism to drive the crankshaft instead completely changed how the robot could move forward: this time the crankshaft is the part that is directly driven, allowing the mechanism to cycle, and move the robot forward using foot traction. The advantage of this is that this driving torque can be multiplied through a reduction gearbox, allowing forward movement at lower windspeeds. For a sail to achieve the same effect, its area would have to be unfurled even further, increasing risk of damage to the structure

from quick gusts from the larger moment arm. It would also have to be made of soft materials which may get damaged in the hostile environment, and make it difficult to manufacture using ISRU methods. With a wind turbine selected, the next step was to determine which type to use, out of a large list of potential candidates.

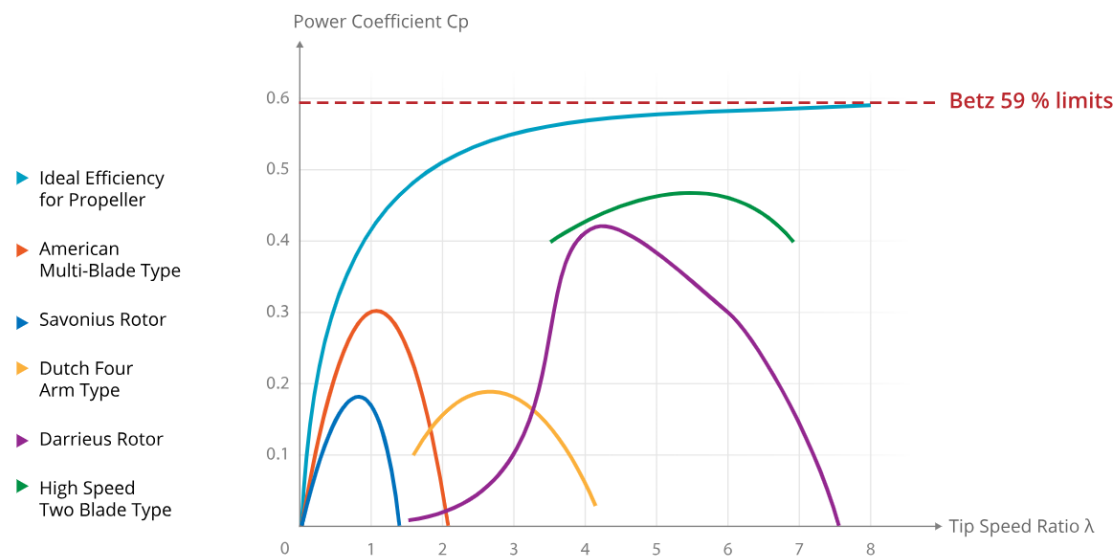
Considering the atmospheric conditions of Titan, and requirement of the robot to walk forward in omnidirectional winds, desirable characteristics of this turbine was that it would be able to rotate in omnidirectional winds, produce usable torque at low windspeeds, and be able to self-start at low wind speeds. This immediately ruled out horizontal axis wind turbine designs, as they are only able to perform nominally when directly facing against the wind direction. This makes them ineffective for this application, as they would be unable to rapidly turn and rotate into instantaneous wind gusts from different directions. They would also add complexity to gearing solutions, trying to extract work from the pivoting turbine shaft. This left vertical wind turbines as the only option, as they are able to perform nominally in omnidirectional winds. Of these, 3 main VAWT designs were identified: the H-rotor and Darrieus lift-type reaction turbines, and the Savonius drag-type impulse turbine. These are shown in Figure 5-12.



**Figure 5-12 Types of VAWT (Mine, 2025)**

While both H-rotor and Darrieus turbines are able to achieve higher efficiencies and torque once up to speed, they have very poor capability to self-start, and produce poor torque at low wind speeds. On the contrary, the low windspeed self-

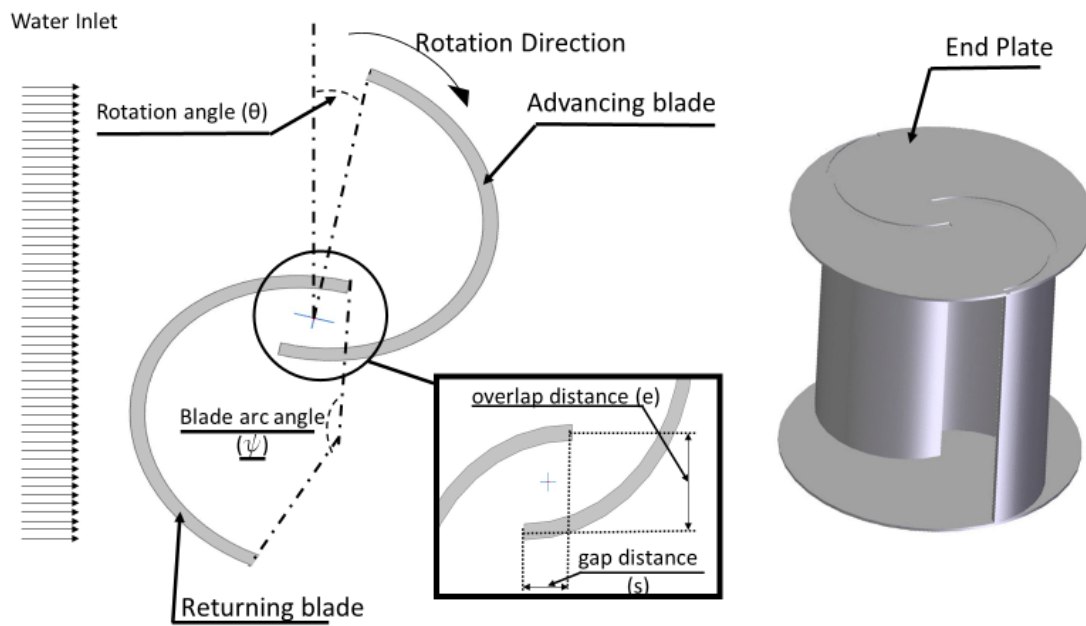
start with high torque capability are the main strengths of the Savonius wind turbine. Figure 5-13 below shows the performance of different turbine types. Darrieus rotor has a higher power coefficient, but only at higher tip speed ratios, which is defined as the ratio of the tangential speed of a turbine blade's tip to the incoming wind speed (Arcara, 2023). The Savonius rotor is not able to match the power coefficient of Darrieus, but is able to start producing usable torque at lower tip speed ratios, which takes priority in this application.



**Figure 5-13 Power coefficient and tip speed ratio of different turbine types  
(Energy Encyclopedia, 2025)**

Hence, the Savonius turbine was selected to be the main wind energy capture mechanism for the robot. Due to its simple design and minimal mechanical complexity, an added benefit was that the inherent design of the turbine was favourable for ground-up additive manufacturing, reducing the number of components and assembly required for the wind capture mechanism.

With the Savonius turbine design selected for the wind energy capture mechanism, the next step was to look at methods to optimise the turbine design to make it more efficient and effective for this application, based on findings from literature, as shown in Figure 5-14:



**Figure 5-14 Design features of the Savonius wind turbine (Kerikous & Thévenin, 2019)**

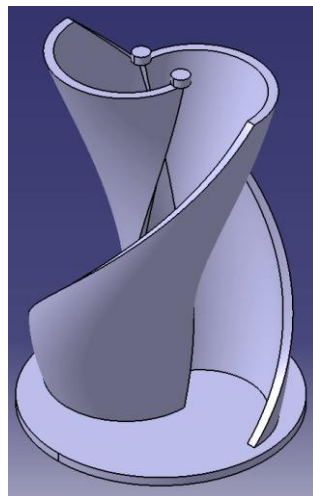
For the first turbine concept, a 2-blade design was considered as it produced the highest torque (Saha et al., 2008). The blade cross section was semi-circular, as is typically expected for turbines of this class, and the design was shaftless to allow airflow to pass through to improve efficiency (Kamoji et al., 2008). With an initial diameter  $D = 80$  mm decided, these are the ratios and sizing of the other features considered:

**Table 5 Turbine 1 design features and dimensions**

| <b>Turbine feature</b>     | <b>Ratio</b>                                     | <b>Length (mm)</b> |
|----------------------------|--------------------------------------------------|--------------------|
| Height, $h$ (mm)           | $1.5 \times D$<br>(Farozan et al., 2025)         | 96.0               |
| Overlap distance, $e$ (mm) | $0.161 \times D$<br>(Kerikous & Thévenin, 2019). | 12.9               |

| Turbine feature            | Ratio                                    | Length (mm) |
|----------------------------|------------------------------------------|-------------|
| Height, h (mm)             | 1.5 x D<br>(Farozan et al., 2025)        | 96.0        |
| End plate diameter, d (mm) | 1.1 x D<br>(Marinić-Kragić et al., 2022) | 88.0        |

Figure 5-15 shows the first turbine design concept. The helical blade twist was set at  $180^\circ$  to improve start-up performance regardless of starting position and uniformly distribute smooth torque to the system during rotation, without buffeting (Damak et al., 2013). A turbine test rig was designed to analyse the performance of each turbine design iteration. Tests were conducted to study the turbines in isolation in different wind conditions without a mechanical load applied, and tested as part of the integrated geared locomotion system. However, with 3 mm thick blades and end plates, it was found that the turbine was too heavy and was lacking in start-up capability due to its high inertia. Integrated into the developed geared and legged systems, it demonstrated poor performance on start up at medium to low wind speeds even with tailwind, and was inadequate and unreliable at start-up for crosswinds and headwinds. Thus, the turbine needed to be redesigned to improve these limitations.



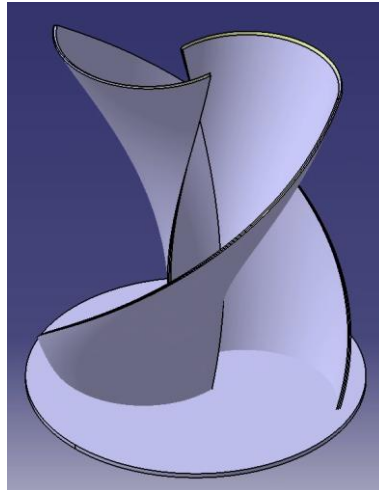
**Figure 5-15 Savonius turbine 1 CAD model without top plate**

The second iteration of the turbine focused even deeper into the detailed design of optimised Savonius turbine design based on literature study, now also additionally considering factors such as blade gap distance, and blade arc angle. The new shaftless blade design had a larger diameter of 100 mm to increase torque and used the following feature ratios as shown in Table 6:

**Table 6 Turbine 2 design features and dimensions**

| <b>Turbine feature</b>                               | <b>Ratio</b>                             | <b>Length (mm)</b> |
|------------------------------------------------------|------------------------------------------|--------------------|
| Height, h                                            | 1.2 x D<br>(Sobczak, 2018)               | 120.0              |
| Overlap distance, e                                  | 0.161 x D<br>(Kerikous & Thévenin, 2019) | 16.1               |
| Gap distance, s                                      | 0.033 x D<br>(Kerikous & Thévenin, 2019) | 3.3                |
| End plate diameter, d                                | x D<br>(Marinić-Kragić et al., 2022)     | 110.0              |
| Blade arc angle, $\psi$ : 160°<br>(Mao & Tian, 2015) | -                                        | -                  |

The thickness of the end plates was reduced to 1 mm to reduce weight. From testing, the second turbine iteration demonstrated significant improvements in isolation on the test rig for self-starting capability at lower windspeeds. The design concept for turbine 2 can be seen in Figure 5-16:



**Figure 5-16 Savonius turbine 2 CAD model without top plate**

Integrated into the existing 8:1 gearing mechanism, where the turbine was taking load, it showed notable improvements in self-starting ability with normal weight and with weight offloading, for the first time being able to demonstrate an ability to walk into headwinds, albeit at high wind speeds. In order for the robot to also be able to walk into headwinds at slower windspeeds, the turbine and gearing ratio would have to be further modified so that the integrated system could generate sufficient torque to overcome the frontal area wind resistance. Further data and findings of both experiments can be found in more detail in Experimental testing of turbine design and Experimental testing of integrated robot system design sections.

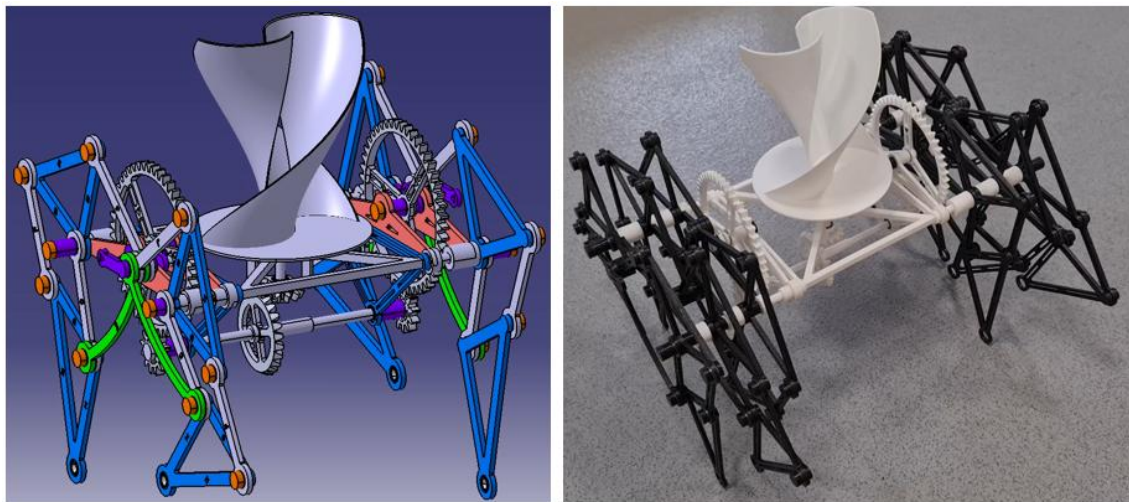
It was also found that the joins holding the centre structure to the ALM frames of the legged mechanism were quite weak, so kept disconnecting during testing. These needed to be redesigned in future prototypes.

However, there were some challenges faced with this turbine design. In the pursuit of achieving perfect turbine feature ratios to maximise efficiency, one factor given less priority was the ease and practicality of the design for manufacture using the available resources. The thin blade design with 1 mm thickness was found to be too difficult to manufacture reliably. Due to the nature of 3D printed build layers, the blade twist meant that layer adhesion between the laminates was poor, and there was no constant central feature such as a shaft to

anchor the layers in place. As a result, for the top layers, the movement of the printer head and print bed meant that there was considerable shaking of the structure, leading to deteriorating print quality for the upper section. The coarse surface and artefacts will have led to additional form drag, reducing turbine efficiency. It also meant that turbine features such as the gap and overlap ratios were preserved poorly, further up.

This became evident when the press-fit top turbine plate, which had been designed with a nominal outcome in mind for the blade shape, could not be fit to the turbine. It was decided that the next iteration of the turbine would sacrifice some feature optimisation in favour of build practicality and quality.

Figure 5-17 shows the CAD model and prototype of turbine 2 installed on WANDER-Bot 2.5:



**Figure 5-17 WANDER-Bot 2.5 integrated system CAD model and working prototype**

Integrated system performance tests showed that the robot was in fact able to self-start in omnidirectional wind conditions, but walking into headwinds required a weight offset to 14%, simulating Titan conditions, and very high windspeeds. See Experimental testing of integrated robot system design for more details. A video of WANDER-Bot 2.5 walking forward with a tailwind can be found by following the link in Appendix B Further Robot Videos and Pictures.

While this outcome was sufficient to meet the project aim, it was desirable to lower the starting threshold windspeed as much as possible, to allow more reliable start-ups in lower windspeeds, with less weight offsetting.

This also allowed an opportunity to assess the implementations of changing gear ratio on the integrated system, so a third prototype model WANDER-Bot 3 was developed.

### **5.2.3 WANDER-Bot 3 design and development**

With the 3 design constituents of the integrated system developed, the purpose of prototype 3 was to optimise the robot integrated system design to allow it to better perform in head and crosswinds at lower windspeeds.

#### **5.2.3.1 WANDER-Bot 3.0 Prototype**

In order to generate higher levels of torque, prototype 3.0 had its gear mechanism redesigned, now with a 16:1 gearing ratio, generating twice the torque output of prototype 2.0 for the given wind conditions. The main way this was achieved was by stepping up the gear ratio of the bevel gears engaging between the turbine shaft and main rotation shaft, now having a 4:1 reduction instead of the 2:1 reduction of the previous design. The spur gears driving the Jansen mechanism remain at 4:1 reduction, leading to an overall reduction of 16:1. In order to accommodate the much larger bevel gear and new turbine design, much of the central support structure had to be redesigned. The joints holding the centre turbine and gearing support structure to the ALM frame were also redesigned to stop them disconnecting during testing.

Prototype 3.0 also featured the third iteration of the turbine design. For this, some blade design features to improve efficiency such as gap ratio and overlap ratio were abandoned, in favour of having a central shaft to increase design rigidity and build practicality. While building on the printer bed, this shaft feature was continuous and constant all the way through the height of the turbine, so served as a good anchor for the twisting blades. The blades themselves were increased in thickness to 1.5 mm, which served as a good compromise between reducing weight, and maintaining rigidity. Combined, these design changes strengthened

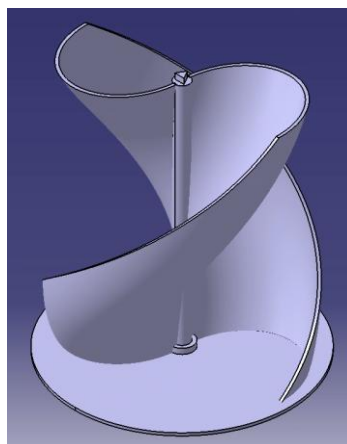
the turbine, and better conserved the feature ratios all the way through without artefacts or delamination, improving its efficiency. The blade diameter was increased to 110 mm. The changes reflected in the other design features are shown in Table 7:

**Table 7 Turbine 3 design features and dimensions**

| <b>Turbine feature</b>     | <b>Ratio</b>                             | <b>Length (mm)</b> |
|----------------------------|------------------------------------------|--------------------|
| Height, h (mm)             | 1.2 x D<br>(Sobczak, 2018)               | 132.0              |
| End plate diameter, d (mm) | 1.1 x D<br>(Marinić-Kragić et al., 2022) | 121.0              |

One notable difference between this turbine design and the previous ones was a change made to the cross-sectional shape of the blade. It instead of semi-circles, they were now instead semi-elliptical, with an eccentricity of 0.6. Now meeting at the central turbine shaft, due to removal of blade overlap, it was expected that this change will decrease the coefficient of drag of the leading blade into the airflow direction, improving turbine torque, efficiency, and self-starting capability at slower windspeeds. (Chan et al., 2018).

Figure 5-18 shows the turbine 3 design concept:



**Figure 5-18 Savonius turbine 3 CAD model without top plate**

Testing the turbine in isolation on the test rig, it was found that it demonstrated improvements in self-start capability at lower windspeeds, and could sustain higher RPMs for the same given windspeed. This was a particular benefit, as the larger diameter also meant that the turbine was also supplying more torque. Integrated into the new 16:1 geared system, the robot was showing vast improvements in start-up at slow winds speeds with tailwinds, as well as crosswinds and headwinds for moderate wind speeds. With weight offloading to 14%, the improvements were better still, with the system now able to self-start at slower windspeeds, between 2 and 3 ms<sup>-1</sup>. Further details of the turbine and integrated testing can be found in Experimental testing of turbine design and Experimental testing of integrated robot system design sections. A video of turbine 3 testing can be found by following the link in Appendix B Further Robot Videos and Pictures.

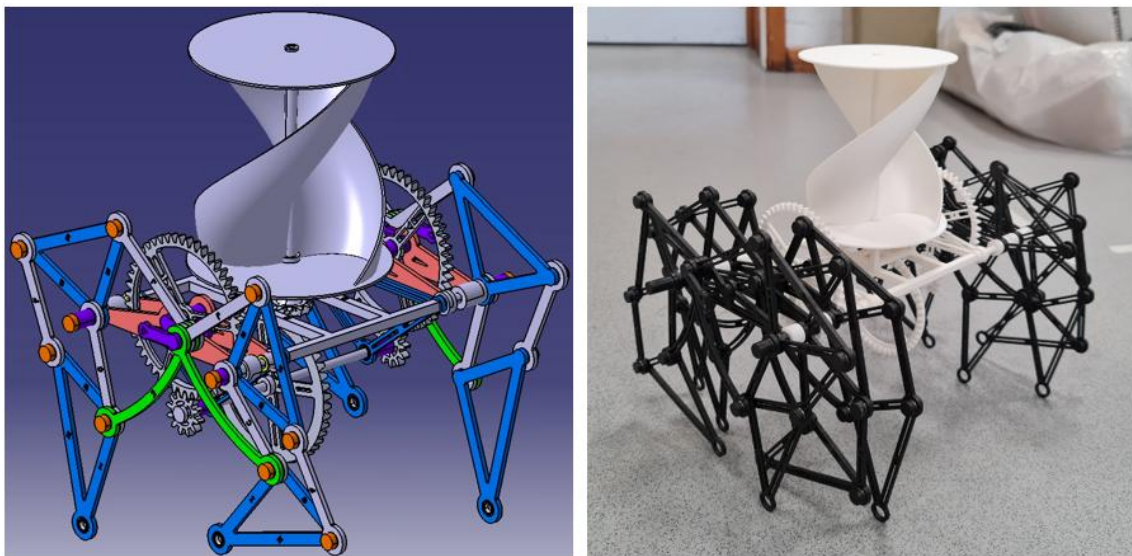
Due to its additional weight, it was found that while turbine 3 could self-start, it took longer to get up to speed than turbine 2. However, once it was running, its weight allowed it to carry more momentum, allowing the robot to ‘coast’ forward for short distances with little to no wind present. This is a particular advantage, as it means that it could thrive better in the chaotic and intermittent nature of wind gusts.

There were still some improvements that needed to be made for the prototype. For instance, the concentric mounts for the turbine shaft kept coming loose, causing precession of the turbine when it was spinning. The number of connections between components in the main rotation shaft caused it to be flimsy, often disconnecting. There was also too much material removed from the large bevel gear to lighten it; as a result, it frequently flexed during rotation, leading to gear slip and disengagement.

#### **5.2.3.2 WANDER-Bot 3.5 Prototype**

This model was a final and iterative update; it aimed to fix some of the structural concerns of the previous prototype. The concentricity mounts were designed to engage with the central structure more firmly with interfacing pins. This removed much of the flexing when the turbine rotated and reduced precession, allowing

the turbine to face the wind more squarely, improving performance and torque. The connections in the main rotation shaft were reduced, making it more rigid and preventing the components from coming loose. The large bevel gear was strengthened by adding material, now with much of its flexing eliminated. This resulted in better gear engagement and reduced slip, allowing the turbine to get up to speed sooner in quick gusts. Figure 5-19 shows the CAD model and final prototype of WANDER-Bot 3.5. A video of WANDER-Bot 3.5 walking forward in omnidirectional winds and meeting the project aim can be found by following the link in Appendix B Further Robot Videos and Pictures.



**Figure 5-19 WANDER-Bot 3.5 CAD model and working prototype**

## 6 Experimental Results and Discussion

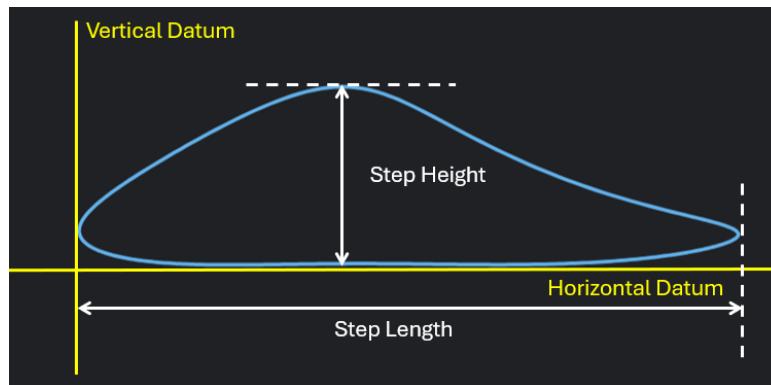
This chapter covers the testing campaign of the robot, aimed to meet objective 4 for performance testing. Experimentation of the integrated robot system includes testing the locomotion mechanism smoothness, turbine mechanism performance, and gearing mechanism.

### 6.1 Testing Robot Walking Gait and Mechanism Smoothness

#### 6.1.1 Experimental Analysis of the Foot Profile

The aim of this experiment was to verify how accurately the constructed robot Jansen mechanism was able to replicate the simulated walking gait, which in turn was made to verify the literature. A more accurate resemblance for the prototype means that the robot's walk is optimised for stability.

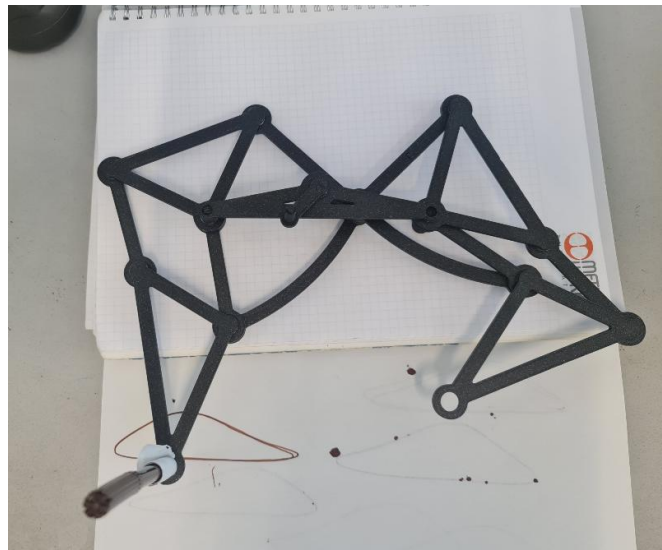
From the motion simulation profile, key features of this shape, such as the step height and step distance could be measured and compared to the experimental results, to assess how accurately the characteristics of the stable Jansen walking gait had been replicated. Figure 6-1 shows the step length and step height parameters on the traced foot profile:



**Figure 6-1 Measured parameters of the Jansen foot walking gait**

A video of the running simulation can be found by following the link in Appendix B Further Robot Videos and Pictures. The experimental setup to trace the walking gait of the foot by the prototype was to use a marker pen which drew out the movement of the leg against a white background. Taking a single leg pair

assembly, the pen was fit to the bearing hole provision for feet in the future. Tape was wrapped around the pen to hold it in place firmly and concentrically when pressed into the hole. The frame was then pressed firmly down on a surface to prevent slippage when rotating the mechanism, and elevated to allow the pen to make continuous contact with the paper. Once set, the mechanism was slowly rotated, allowing the pen to draw out the track traced by the foot. The set-up for this can be seen in Figure 6-2.



**Figure 6-2 Experimental set-up to draw prototype Jansen walking gait**

Completing a couple of rotations helped to confirm that there were no slippages while the cycle was being completed; any minute slips would become immediately evident in the walking track of the leg, from poor line overlaps. Once drawn, the ratio of the key features of the drawn track could be measured and compared against the simulations. Several shape profiles were drawn and measured, using both legs, with their results averaged to ensure reliable results. The data from these tests can be found in Table 8:

**Table 8 Simulated and Experimental values of Jansen walking gait paramaters**

| Feature                       | Motion Simulation | Experimental |
|-------------------------------|-------------------|--------------|
| Crankshaft length, $l_0$ (mm) | 24.0              | 24.0         |
| Step length, $l_s$ (mm)       | 108.0             | 109.0        |
| Step height, $l_h$ (mm)       | 30.0              | 30.0         |

Table 9 below shows a comparison of the ratios from literature, motion simulation track, and experimental track of  $l_0$  against  $l_s$  and  $l_h$ :

**Table 9 Feature ratios of Jansen foot walking gait from literature, simulation, and experimental result**

| Feature Ratio                      | Literature<br>(Patnaik &<br>Umanand,<br>2016) | Motion<br>Simulation | Experimental<br>Result |
|------------------------------------|-----------------------------------------------|----------------------|------------------------|
| Crankshaft length ratio, $l_0/l_0$ | 1                                             | 1                    | 1                      |
| Step length ratio, $l_s/l_0$       | 4.5                                           | 4.5                  | 4.54                   |
| Step height ratio, $l_h/l_0$       | 1.5                                           | 1.25                 | 1.25                   |

The general shape profile of the simulation and experimental result closely resembles the literature with qualitative analysis with the points of foot raising, landing, and non-symmetrical peak. However, a quantitative analysis between the literature value and simulation shows that although the step length ratio matches, there is a reduction in the step height ratio. This was seen as acceptable for prototyping, as a less pronounced peak would mean a smoother cycle when the leg approaches maximum height, albeit at the expense of a reduced maximum ground clearance for the leg for future terrain performance testing.

As shown in the table above, the experimental results very accurately match the general shape characteristic and feature ratios as predicted by the simulation,

demonstrating that the robot is following the optimised walking gait of the Jansen mechanism with optimised stability.

This was further complimented by the additional stability provided by the 120° offsets for the other leg pairs; the robot never showed signs of stumbling from a lack of support. This meant that any given moment, there was always at least one leg taking the support stance of the robot and bearing its weight in each corner.

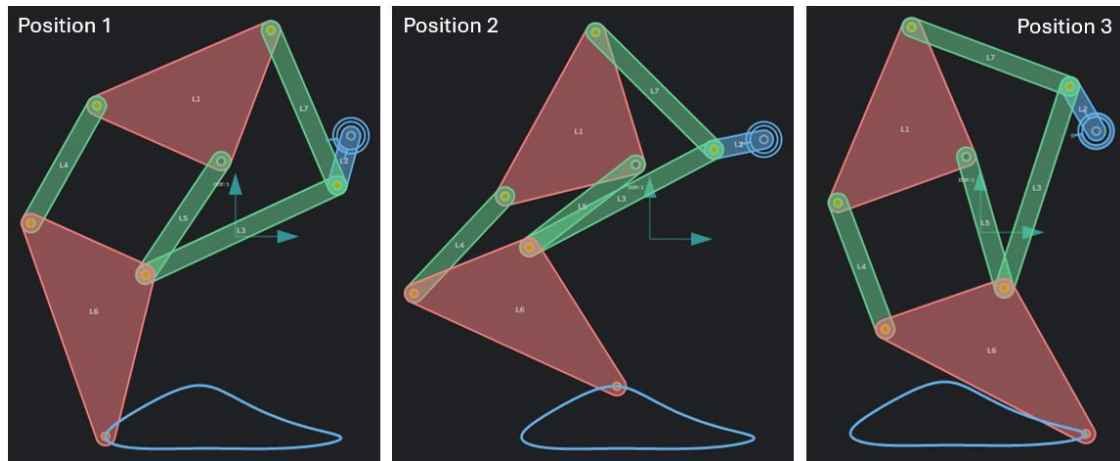
### 6.1.2 Experimental Analysis of the Jansen Locomotion Mechanism Smoothness

Another aim of the walking gait testing was to assess the smoothness of each mechanism cycle as it was rotated to identify if it required a uniform torque throughout, or if there were moments where the torque requirement spiked. From running each cycle, it was found that there are 3 main resting positions of the mechanism, which were between 3 instances where rotation resistance peaked, requiring more torque to rotate from the crankshaft. The points of highest observed resistance from the mechanism have been marked below in Figure 6-3:



**Figure 6-3 Identified positions of increased resistance in walking gait from test**

These maximums appear when the Jansen leg is in the following leg configurations shown in Figure 6-4:



**Figure 6-4 Motion simulated Jansen leg configurations at each resistance spike**

As the Jansen linkage walking gait is defined by multiple pivot points, its instantaneous mechanical advantage will vary constantly depending on the crank angle. The highest point of resistance in the cycle is when the leg reaches position 2. Looking at the link geometry in this position, this is likely due to the collapsed leg mechanism 'locking up' because the crank angles between the linkages are either too acute or too obtuse, causing linkages to have near-straight alignments. This reduces the effect of the lever arms between the linkages and produced mechanical torque, meaning more work has to be done by crankshaft to eventually 'break' through the extrema and continue the cycle.

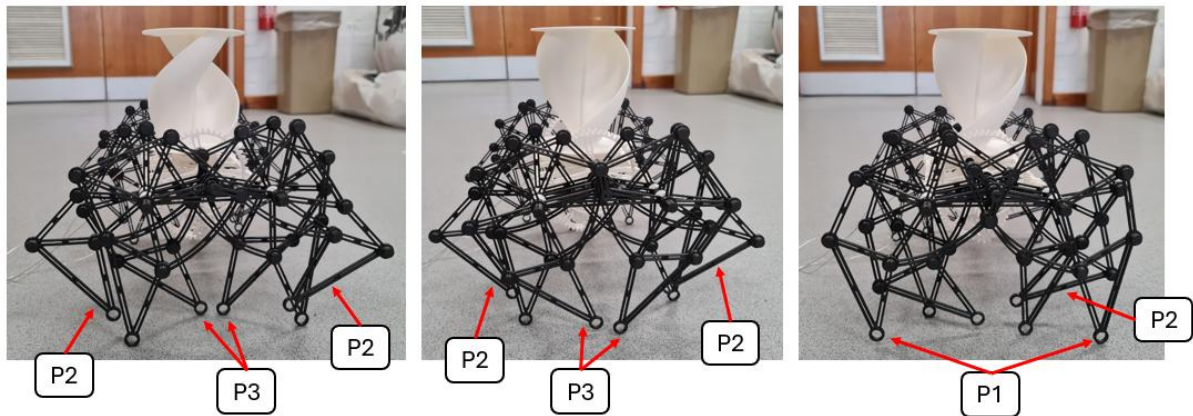
The motion simulation shows that position 2, where the foot changes direction, is also the point at which most of the joints reverse their rotation direction. At this point the foot also carries the most speed, and change in acceleration when going through each cycle. In the real world, as bearings have been used in the joints, there may be some inertia in bringing their rotation to a stop at this speed and suddenly reversing their direction. Furthermore, at position 2, the full weight of the leg is lifted off the ground, and the rotating crankshaft has to do the most mechanical work to bear its full weight load and raise the centre of mass to its maximum point of potential energy.

Positions 1 and 3 have a similar level of resistance, but is substantially less, compared to when the cycle reaches position 2. These increases are likely because these are also points where the foot changes direction, causing some

of the bearings to stop and reverse direction to continue the motion. These are also the points where the foot impacts the ground depending on the cycle direction, and where the foot gets lifted up, once again causing the mechanism to bear its weight load and begin converting it back to potential energy until the maximum height is reached. At the point of foot ground impact, the mechanism transitions to the flat profile. Here, there is a sudden deceleration in the vertical velocity, causing load, and a sudden increase in friction as the foot gains traction with the ground to 'push' the robot forward.

Installed together in an assembly, the 120° phase differencing between the leg pair modules on each side means that these instantaneous extrema are less pronounced. Combined with the reduction gearing ratio, which multiplies the produced torque, the integrated system smooths out these resistance peaks to a more continuous resistance and torque requirement for the system. This smoothness is most evident when the robot is moving in higher windspeeds, and the integrated system carries more momentum.

When gently pushing the robot at slow speeds, these individual extrema are hardly noticeable, but after propelling the robot forward using wind or pushing by hand and allowing it to coast, it typically comes to rest when the legs assume one of these positions, where the momentum of the coasting robot is no longer able to overcome the resistance of the local maximums for some of the leg configurations. Figure 6-5 below shows 3 typical scenarios where the robot mechanism has come to rest after coasting, with the legs typically in one or more combinations of leg position 1, 2 or 3 (P1, P2, P3). The leg modules on the other side of the turbine and centre structure are symmetrical to this. A video of the Jansen mechanism smoothness testing can be found by following the link in Appendix B Further Robot Videos and Pictures.



**Figure 6-5 Resting leg positions of WANDER-Bot after coasting**

## **6.2 Experimental testing of turbine design**

The aim of this experimental analysis was to assess the behaviour of each wind turbine iteration design for given wind conditions to identify progress in the turbine's performance characteristics such as start-up behaviour and RPM at given windspeeds. The turbines were tested in isolation without load so that their performance metrics could be gathered in absolute terms without influence from the gearing system. Higher RPMs are desirable for lower windspeeds, as it means that with load, the turbine is more likely to self-start with weaker airflows.

A turbine test rig platform was designed and manufactured to assess the performance of different iterations. It featured a large base which could be clamped to the table surface to prevent the rig and turbine from being blown off during experiments, and bearing mounts to support the turbine shaft and hold it in a concentric position to prevent turbine procession in the airflow caused by the misalignment. Measuring markers were also stuck to the floor, in 20 cm increments, with an origin marker where the fan would be placed. The markers extended up to 3.2 m away from the fan, as this was the point where the desired dynamic pressure to replicate typical Titan wind conditions could be replicated, using the atmospheric conditions of Earth.

The variables for the experiment were as follows:

Control variables:

- The windspeed and distance away from electric fan
- The test rig stand base for turbine mounting
- The mechanical load experienced by the turbine when rotating (bearing resistance only on the stand)

Independent variables:

- The turbine design iteration being tested

Dependant variables:

- The measured self-started RPM of the turbine at the given distance

The test procedure of the experiment was as follows:

1. Connect and power on the fan, placing it at the origin marker at the start of the measuring strip. Tilt the fan to ensure the generated wind blows roughly parallel to the floor.
2. Use an anemometer to measure the windspeeds at each 20 cm increment from the origin line. There is no purpose in measuring wind speed at the origin directly in front of the fan grille, as the airstream would be turbulent and buffet, caused by the rotation of each blade, resulting in unreliable readings. Allowing some distance before the first measurement allows the airflow to settle after passing through the grille, allowing it to become more stable and laminar. Take 3 separate recordings at each distance and average the readings. Allow the airflow to settle before taking readings. When close to the fan, measure the wind speed at the outer edges of the blades, as the central hub is expected to supply less wind speed due to its slower rotation.
3. Mount the turbine being tested to the test rig stand shaft and place it at the first 20 cm marker, allowing it to start up. Turbine positions near to the fan should be placed closer to the outer diameter of the drum, where windspeed is highest. Placing it in the path of the centre hub of the drum will yield lower windspeeds.
4. Once up to speed, start a stopwatch on the side and capture the rotation of the turbine for a few seconds using a slow-motion camera.

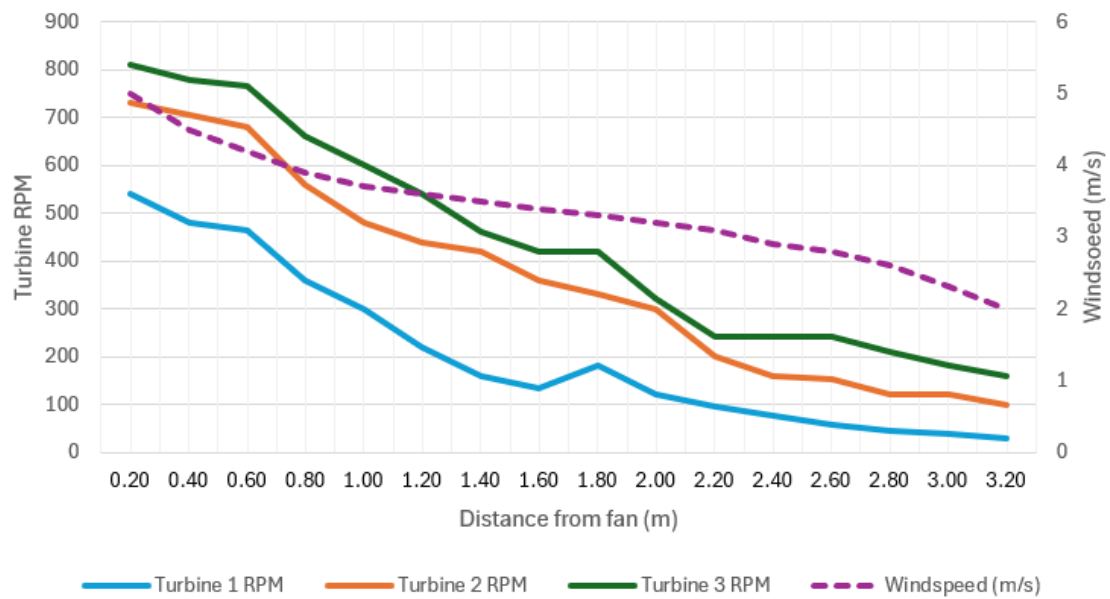
5. Repeat the test at the same marker and take a second recording.
6. Move to the next 20 cm marker and repeat the process till the full distance of the markers have been tested.
7. Repeat the experiment for the different turbine designs
8. Analyse the slow-motion video recordings to determine how many full rotations the turbine completed in the time it was recorded; convert this to an RPM number. Take the mean RPM for each turbine at each distance from the repeat trials.
9. Plot RPM against the distance from the fan to compare their performance at different wind speeds.

The experimental set-up is shown in Figure 6-6. A video example of the turbine testing can be found by following the link in Appendix B Further Robot Videos and Pictures.



**Figure 6-6 Experimental set-up for turbine performance testing**

Figure 6-7 below shows the results following the experimental procedure above. The RPM of each turbine iteration has been plotted for each given distance from the fan, along with the recorded windspeed at each distance, presented on the secondary axis.



**Figure 6-7 Graph showing RPM of each turbine design at given distances from fan and different windspeeds**

The detailed design features and evolution of the 3 turbine designs developed for this project can be found in the Robot Design Evolution section. Running tests on the turbines without mechanical load show that all 3 turbine designs are able to self-start and produce RPM at all the tested windspeeds. This includes the low  $2 \text{ ms}^{-1}$ , replicating typical Titan wind gust dynamic pressure. This in itself is a success, as it means that the Savonius vertical wind design with the  $180^\circ$  twisted helical blades was an effective design solution for self-starting capability, even at low windspeeds, which verifies the literature. They were all able to start regardless of their starting position when facing airflow. Its ability to self-start with the mechanical load applied for the robot locomotion will be tested for the integration tests, see Experimental testing of integrated robot system design section.

As shown by the graphs, as expected there is a steady decline in RPM as distance increases from the fan, matching the falling windspeed. Further test runs and more frequent sampling points would be needed to verify if this relationship is exactly linear. Though all turbines are able to self-start, turbine 1 consistently demonstrates the lowest RPM in all windspeeds. This is the smallest diameter turbine, but coupled with the knowledge from literature that smaller diameter

turbines inherently have lower torque and higher RPMs for a given windspeed, it indicates that the design has a poor conversion efficiency. This design would produce the least mechanical work when integrated into the geared system.

Its mass creates more inertia leading to a slower start-up, but it was noted that it also better-preserved angular momentum when the wind load was removed, continuing to rotate for longer periods of time than the other turbine designs.

The thinner turbine 2 design removes much of the mass from turbine 1, meaning less force is required by the wind to match the RPMs of turbine 1. Thus, it is consistently able to achieve significantly higher RPMs, on average around 120% higher RPM gains considering all wind speeds. This is despite having a larger blade diameter, which also means that it is generating more torque. This is the manifestation of blade feature optimisations from literature, such as the introduction of gap ratio, blade arc angle, and refinement of existing features such as overlap distance and end plate diameter. There have been some efficiency losses as the preservation of these features deteriorated along the height of the turbine due to progressively poorer print quality, but its notable performance improvements made it a better candidate WANDER-Bot 2.

Turbine 3, which introduced a central shaft and removed some optimised features such as overlap and gap distance in favour of build quality, still consistently showed the highest RPMs in all wind conditions. On average, the data shows that in the measured wind conditions, it had a 192% faster RPM than turbine 1, and a 30% higher RPM than turbine 2.

This is despite having the largest blade diameter, meaning it was producing the highest torque and mechanical work. One reason for this may be due to its new elliptical blade cross-section, which allows a larger differential between the drag coefficients of the leading and trailing blade faces, improving blade efficiency. This was also evident in its start-up confidence, it was able to get up to speed faster than turbine 2, despite having a higher mass. Its greater mass than turbine 2 due to the strengthening of the structure also allowed it to possess more angular momentum once the wind stopped blowing.

Combined, these factors made it the most ideal candidate for WANDER-Bot 3, which required the most torque and mechanical work the system could produce in order to allow the robot to walk more readily in low and moderate speed headwinds and crosswinds.

While RPM is one metric for measuring turbine performance and was able to be determined experimentally, in the future if more resources were available, experimentally determining other factors such as torque output at the turbine shaft, would provide more accurate data on the capability and efficiency of each turbine design.

### **6.3 Experimental testing of integrated robot system design**

The aim of this experiment was to study the performance of the robot start-up in different wind conditions, considering windspeed and direction. Incorporating headwinds, crosswinds, and tailwinds at different wind speeds, the tests aimed to gather and compare experimental data on the integrated system self-start threshold, before the robot began to walk forward.

Unlike the turbine tests which were completed in isolation without consideration of mechanical load and gear ratios, this evaluated the performance of the system as a whole.

Using Titan as one of the test scenarios, with its 14% the gravitational field strength of Earth, the study also incorporated simple weight offsetting methods, to study their effect on system performance. This experimental set-up used the same markers and fan used in the previous turbine experiment, but this time keeps the robot at the origin, and moves the fan to different distance markers. From here, it was easier to identify the distance and windspeed limit when the windspeed drops beyond the self-start capability of the robot. A rough and firm surface terrain was used for robot testing, to simulate Titan's frozen plains.

The variables for the experiment were as follows:

Control variables

- The windspeed and distances at which the electric fan is held.

- The surface terrain on which the tests were conducted.

#### Independent variables

- The robot prototype and turbine combination being tested.

#### Dependant variables

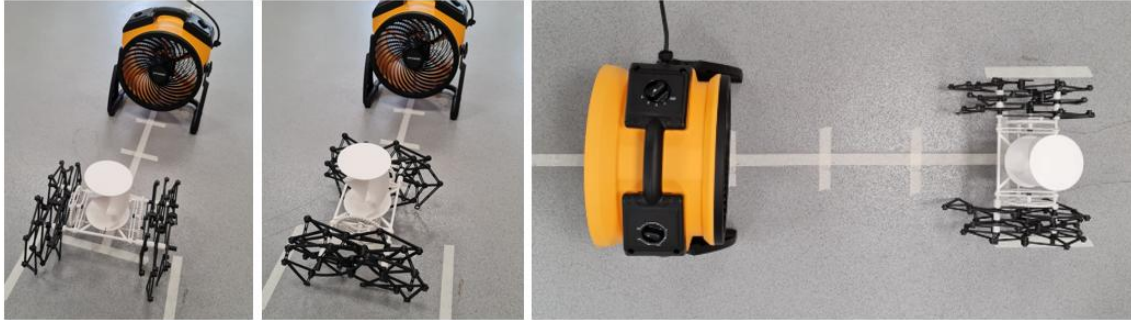
- The recorded distance at which the robot self-starts and begins to walk forward.

The test procedure of the experiment was as follows:

1. Place first robot prototype on the floor marker origin, oriented to be able to walk forward in a tailwind direction.
2. Place the fan on the first 20 cm marker, aimed at the robot. Aim to keep airflow parallel to the ground. For the first few increments, align the turbine with the edge of the fan drum to get maximum windspeed.
3. Record if the turbine was able to self-start and the robot was able to take a few steps forward. Repeat trial to confirm result.
4. Move the fan to the next marker and repeat the trial.
5. Repeat the experiment for each consecutive marker until the end of the marking strip has been reached.
6. Next orient the robot side-on to the airflow direction to study its crosswind start-up capability and repeat experiment.
7. Repeat process again with the robot oriented for a headwind.
8. Repeat steps 2 to 7 with the next robot prototype and turbine combination.
9. Next place the robot back in its starting position at the origin and place it on a mass balance. Record the initial weight of the robot.
10. Attach a string to the sides of the robot frames, and calculate the expected weight at 14%.
11. With the fan running, take up slack in the strings until the weight of the robot matches the weight equivalent of Titan and hold.
12. Repeat experiment steps 2 to 8 with weight offloading and record if the robot self-starts at each distance.

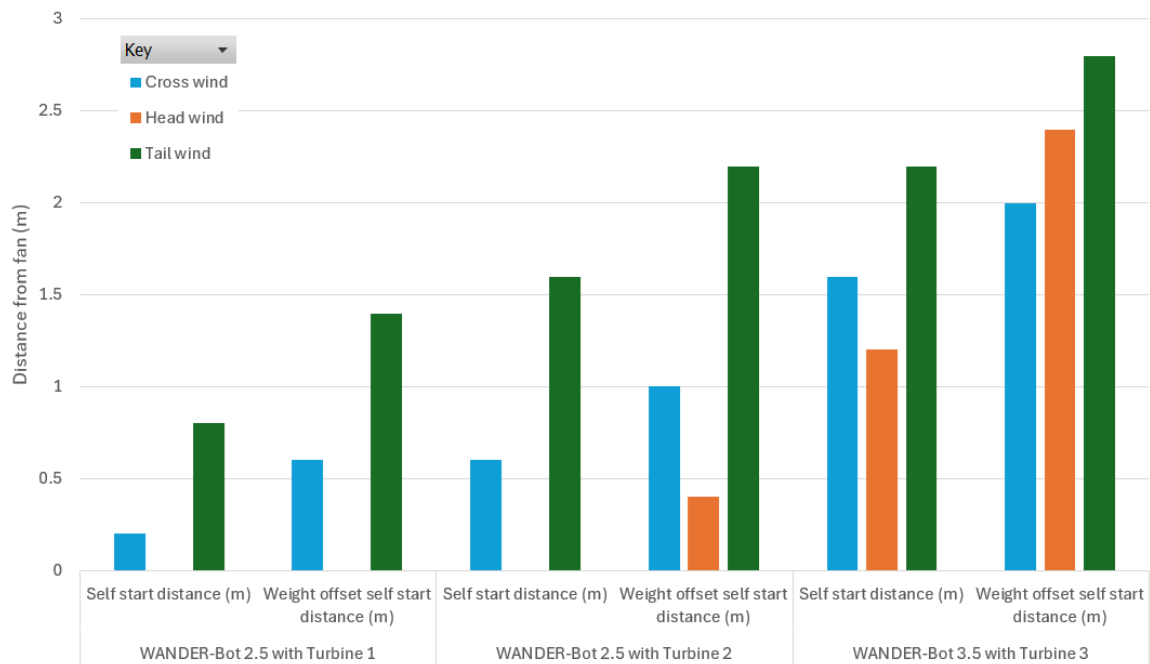
13. Plot the maximum distance that the robot can achieve self-start, for each tested wind direction, considering normal weight and 14% weight.

The experimental set-up for this is shown in Figure 6-8:



**Figure 6-8 Experimental set-up for integrated robot testing**

Figure 6-9 below shows the experimental results of the testing:



**Figure 6-9 Experimental results for start-up thresholds windspeeds at crosswind, headwind, and tailwind directions for different robot-turbine combinations**

As shown by the data, there are drastic improvements to robot performance with each iteration. WANDER-Bot 2.5 with Turbine 1 shows very poor start-up capability, with its normal weight requiring high wind speeds to move with a tailwind, and very high windspeeds to start moving with a crosswind. With a

weight offset to 14%, the robot shows 75% distance increase from the fan for self-start tailwind conditions, and 200% increase for crosswinds. However, it demonstrates no capability to start with a headwind, as the turbine and gearing mechanism are simply unable to produce sufficient torque to overcome the frontal air resistance on the robot.

The next iteration showed the vast improvements with the upgraded Turbine 2 installed, but with the same 8:1 gearing ratio. Even with full weight on the ground, its new turbine allowed the system to match the starting distance of WANDER-Bot 2.5 with Turbine 1 with weight offset, in crosswind conditions, and outperformed it in tailwind conditions. Weight offsetting for WANDER-Bot 2.5 with Turbine 2 brought improvements to the self-start distance as was seen in the first integrated system. Crucially, these conditions allowed the robot to self-start for the first time, facing directly into headwinds, albeit at high windspeeds.

While this was enough to meet the project aim, it was desirable to lower the windspeed for this threshold to be met, for a more reliable lower windspeed start-up without the need for weight offsetting. To achieve this, the integrated robot system needed to be able to generate more torque, combining factors such as a redesigned turbine, and redesigned gearing ratio, which could achieve a higher reduction.

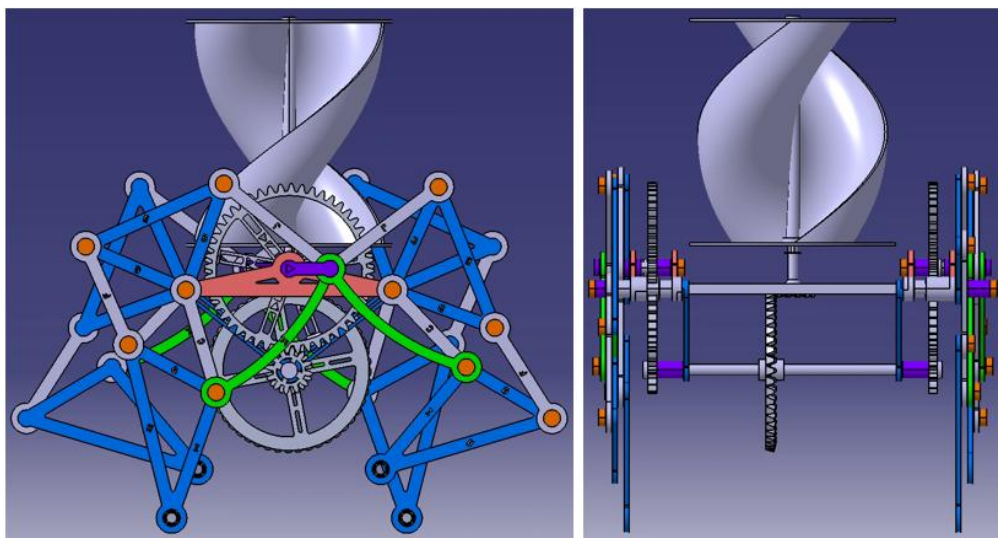
WANDER-Bot 3, with the 16:1 gearing ratio, and new Turbine 3 design, definitively demonstrated the best starting performance in all conditions due to the significantly larger torque generated by the system from the incoming airflow. The largest gain is the system's ability to now confidently self-start facing direct headwinds without weight offload at moderate wind speeds:  $3.6 \text{ ms}^{-1}$ . With weight offload, this reached as low as  $2.9 \text{ ms}^{-1}$ . A video of WANDER-Bot 3.5 walking forward in omnidirectional winds and meeting the project aim can be found by following the link in Appendix B Further Robot Videos and Pictures.

With full weight on the ground and tailwind conditions, WANDER-Bot 3.5 matches the weight offloaded performance of WANDER-Bot 2.5 with Turbine 2, but shows drastic improvements for crosswinds and headwinds.

With the weight offset to 14%, WANDER-Bot 3.5 brought further starting distance improvements, with its tail, cross, and headwind start-up speeds being  $2.6 \text{ ms}^{-1}$ ,  $3.2 \text{ ms}^{-1}$ , and  $2.9 \text{ ms}^{-1}$  respectively. While these are still higher than the  $2.105 \text{ ms}^{-1}$  equivalent windspeeds for typical dynamic pressures expected on Titan's surface, it proves the capability of the early concept system to work in the environment, if more resources were allocated to refining and maturing the system.

With weight offset, one notable observation was that the system self-started at a lower windspeed for headwind than for crosswind, which unexpectedly breaks the previous trends. Repeating the test reproduced the same results. One reason for this may be that the frontal area of the robot facing into headwinds is significantly less, as it is only the thickness faces of the Jansen linkages, gears, and central support structure. With less obstruction of airflow to the turbine, it allows the system to produce enough torque to overcome its frontal drag, and allow the robot to walk forward.

However, for crosswinds, the area exposed to the wind from the Jansen linkage assembly and gears is significantly greater, as it is square to their width faces. Due to obstruction of airflow reaching the turbine, this likely reduces the efficiency and torque of the robot for crosswind self-started motion. Comparison of the front and side profile can be seen in Figure 6-10.



**Figure 6-10 Side and frontal profile of WANDER-Bot 3.5**

It was noted that since this system has the largest mass of the prototypes with its larger turbine and gearing system, it possessed the most momentum walking forward, allowing the robot to coast for noticeably longer distances without wind loads. However, the exact impact of this on the robot's walking ability would need to be measured using other experimentation methods, along with its walking velocity at different windspeeds.

It should also be noted that the floor surface on which the robots were tested was a rough and firm, which may be an acceptable representation of Titan's firm frozen plains. Preliminary testing of a smoother surface shows that with less friction, the robot is able to walk longer distances and potentially even self-start at slightly lower windspeeds, but these would need to be verified with further tests.

### **6.3.1 Experiment Findings Summary, Limitations and Proposals for Improvement**

As shown by the experimental results, the prototypes accurately replicate the Jansen mechanism walking gait, matching the simulations which verified the literature, to trace the optimal foot walking shape to maximise stability. The 120° phasing of the leg pairs allows the robot to have support in its 4 corners at any given time, keeping the centre structure stable and parallel to the ground, making it suitable for future payload installation.

Experimental testing of each turbine iteration helped to analytically show improvements with each design, eventually settling with turbine 3 as the best option of the designs so far, due to its consistently high RPM at all windspeeds tested. Considering RPM at different windspeeds is only one performance metric to identify improvement, but in the future experimental rigs should be set up to measure the produced torque at the turbine shaft.

As for the integrated system, the tests showed the success and advantage of WANDER-Bot 3.5 with the increased crankshaft torque, due to the improved turbine and gearing mechanism. It convincingly demonstrated capability as was the objective of the design, for the robot to walk forward in omnidirectional winds. However, despite its capability, further work still has to be done for future design

iterations to enable it to self-start and walk forward in low Earth windspeeds to simulate typical Titan wind gusts in all wind directions. Some solutions for this are as follows:

- Redesign the gearing mechanism to have even higher gearing ratios, putting less mechanical load on the turbine. Experimental tests on all 3 turbine designs in isolation have shown that they are in fact capable of self-starting with minimal load for the typical Titan wind conditions.
- Upscale the entire model so that factors such as bearing resistance and friction with the walking surface have a proportionally smaller impact on walking resistance.
- Analyse and test more turbine designs to strike a balance between blade feature optimisation and build quality.
- Evaluate if there is possibility for the system to have multiple turbines controlling each side of the robot to reduce mechanical load on each turbine.
- Investigate the feasibility of hybrid turbines which can combine self-starting capability at low wind speeds with torque production to move the robot forward once up to speed.

Other work to take this project further to produce improved outcomes include:

- More accurate simulation of Titan's conditions to more accurately study the robot's capability. This includes consideration of the temperature cycles expected on Titan's surface, having a testbed that replicates Titan's terrain, and more accurate weight offloading systems. Atmospheric conditions can be better replicated using a pressure chamber; Titan has a 1,470 mbar ambient pressure compared to Earth's 1,013 mbar (NASA, 2018) (SKYbrary, 2020). The 4.4x denser atmosphere can be replicated using a heavy non-toxic gas, such as sulphur hexafluoride, which has a density of  $6.04 \text{ kgm}^{-3}$ , compared to air's density of  $1.225 \text{ kgm}^{-3}$ , making it 5x denser (AGC Chemical Company, 2025). It can be diluted with air or nitrogen to achieve the 4.4x higher atmospheric density goal inside the pressure chamber.

- Investigation into feet design to improve robot stability and traction. At the foot section of each leg, hole provisions have been included in the design in the future to add bearings or rods for different foot designs. These can be tested for different terrain types expected on Titan to assess their performance. This will especially be able to reduce any slide slippage of the robot for crosswinds.
- While walking speed was not as high of a priority for this wandering robot, experimental tests to study its walking speed and ability to coast at different windspeeds would be an effective way to evaluate the performance of the system.

## 7 Conclusion and Future Work

Revisiting the project aim, the goal of this project was to investigate and experimentally develop an early design concept for a fully mechanical robot locomotion design, directly powered forward by omnidirectional wind energy, aiming to address the problem statement of reducing locomotion power demand, cost, and storage requirement. The project achieved this by proposing the integrated WANDER-Bot design, consisting of a Savonius turbine wind energy capture mechanism, torque multiplication reduction gearing mechanism, and Jansen mechanism locomotion solution. To save cost and improve maintainability, it used simple linkages and assembly methods, additively manufactured with 3D printing to demonstrate the future ISRU manufacturing potential of the design, which minimises the volume and mass budget for the locomotion system in the mission. Being a purely mechanical solution for added robustness in hostile conditions, the Savonius turbine solution allowed the system to achieve forward motion in all wind directions, while demanding no electrical power for locomotion.

The report covered the systematic approach to achieving this solution by setting objectives, including conducting a literature study of existing solutions and their limitations, identifying existing and future mission proposals using air as a medium for locomotion, and identifying refinements and optimisation of the Jansen mechanism. It also researched the atmospheric and environmental conditions of Titan to create a test scenario which could be reasonably replicated within the constraints of the project. From this, the knowledge gap and contribution of this research is recognised, being used to generate the project design drivers and requirements.

The design evolution and progress of the WANDER-Bot design before achieving the final solution was documented, to address each design requirement and meet the aim. This included the development and testing campaign, which covered running simulations, manufacturing iterative prototypes of the turbine, walking mechanism, gearing mechanism, and integrated solutions. Experimental tests included experimental analysis of the Jansen walking mechanism to ensure

smoothness and stability, comparing its accuracy to expected results from literature and simulations to ensure maximum stability was achieved. Performance tests were also conducted on the turbine, testing RPMs at different windspeeds, and integrated system iterations, such as activation windspeed for self-start. These tests considered an environment which loosely simulated Titan, with firm terrain, various windspeeds to create equivalent dynamic pressures, omnidirectional winds, and gravitational field strength replication with weight offset.

As the design concept and maturity is still in its infancy, it can be concluded that at this stage, the project is not yet ready for planetary exploration applications such as Titan, but proves the feasibility of the general concept of a low-cost, low-power, low-storage, easy maintenance locomotion solution for future planetary applications. The report proposes further improvements in future iterations which would allow the robot to further lower its self-starting windspeed, and improvements to make to test conditions more representative of the environmental conditions.

The following are proposals for future work and research on the robot to increase its design maturity, making it more suitable for planetary exploration:

- Study the resistance extrema in the Jansen mechanism and investigate ways to minimise this, to maximise the smoothness of the robot motion. This could be through in-phase elliptical gearing which can provide instantaneous spikes in torque where the resistance is present, or through changing link ratios to adjust walking gait with less variation between the resistance peaks.
- Investigate the Jansen linkage ability for traversing rough terrain and obstacles. The current Strandbeest Jansen design is optimised for level walking on sandy surfaces, but the link ratios may need to be adjusted to change the walking gait to allow the foot to lift higher off the ground to avoid larger obstacles, compromising some walking stability in favour of ground clearance, for rougher terrain traversal. Some stability can be

retained by increasing the number of legs and adjusting the phasing between them.

- Adjustable walking speed and torque of the robot. Investigate the feasibility of motorised gearbox that can change gearing ratios as required for exploration and terrain traversal requirements. Faster walking speeds may be useful for exploring flat sandy terrain quickly, but a slower walking speed and higher torque may be required for the same wind conditions when the robot encounters slopes and rougher terrain. Alternatively, this method allows the robot to lower its self-start windspeed ability by increasing its gear ratio when windspeeds are very low, and reduce the gearing ratio to keep its walking speed low during storms with fast windspeeds, to protect its components from damage and wear.
- Long-term tests of temperature and climate on robot's performance. Investigate how the cryogenic temperatures of Titan would affect the locomotion system, if wind conditions were not favourable for movement for prolonged periods of time, investigate if the mechanism would be able to continue movement without freezing, or if heating elements would be needed to thaw the ice and resume operations.
- Introducing controlled steering capability into the robot. The current WANDER-Bot design is only able to move forward and steer chaotically based on wind gusts and instantaneous increases in resistance from terrain features interfering with its leg mechanism. Solutions for this may be having 2 turbines, one for each side, with an electronically controlled braking system on the turbine which allows the other side to pivot and turn the robot to face a new direction. An alternative method could be to motorise the engagement of the spur gears rotation the leg mechanism, disengaging them on one side when the robot needs to pivot. For both scenarios, a small voltage electronic system would be needed, but it would consume very little energy for a short period of time and still allow the system to maintain its naturally powered mechanical locomotion philosophy, still offsetting the majority of the typical power demand for existing locomotion systems.

- Basic robot perception and autonomy, with obstacle avoidance and basic autonomous navigation. Titan is on average 80 light minutes away from Earth, and not feasible to have real time steering of the robot when obstacles and harsh terrain features are encountered (NASA, 2018). Basic sensors and processing with low power computing would allow the system to follow path plans, while being able to reactively avoid obstacles, using its electronically steered mechanisms.

While Titan was the prime future candidate for application of the WANDER-Bot design, its inherent qualities of being resilient in hostile applications, being low cost, requiring low power, and having an easy on-site assembly design makes it applicable to multiple environments, including even for Earth-based applications. With new capabilities introduced such as steering, variable ratio gearing or robot perception and autonomy, in the future, locomotion solutions such as WANDER-Bot could even be used in hostile environments such as Antarctica for data gathering or exploration. The system also has potential in swarm collaborative technology for fast low-cost exploration of planetary terrain.

## References

AGC Chemical Company. (2025). *SF 6 basic physical properties*.

[https://www.agc-](https://www.agc-chemicals.com/file.jsp?id=jp/en/products/pdf/SF6_EN04.pdf)

[chemicals.com/file.jsp?id=jp/en/products/pdf/SF6\\_EN04.pdf](https://www.agc-chemicals.com/file.jsp?id=jp/en/products/pdf/SF6_EN04.pdf)

Analytic Physics. (2020). *The Jansen Linkage*. Analyticphysics.com.

<https://analyticphysics.com/Diversions/The%20Jansen%20Linkage%20in%20LEGO%20Mindstorms.htm>

Arcara, J. (2023, February 24). *Tip Speed Ratio: How to Calculate and Apply*

*TSR to Blade Selection*. Windy Nation Inc.

<https://www.windynation.com/blogs/articles/tip-speed-ratio-how-calculate-and-apply-tsr-blade-selection>

ARKA. (2025). *Solar Irradiance & Insolation for Solar Designers- Arka360*.

Arka360.com. <https://arka360.com/ros/solar-irradiance-concepts>

Balaram, J., Aung, M., & Golombek, M. P. (2021). The Ingenuity Helicopter on the Perseverance Rover. *Space Science Reviews*, 217(4).

<https://doi.org/10.1007/s11214-021-00815-w>

Banfield, D., Spiga, A., Newman, C., Forget, F., Lemmon, M., Lorenz, R.,

Murdoch, N., Viudez-Moreiras, D., Pla-Garcia, J., Garcia, R. F.,

Lognonné, P., Karatekin, Ö., Perrin, C., Martire, L., Teanby, N., Hove, B.

V., Maki, J. N., Kenda, B., Mueller, N. T., & Rodriguez, S. (2020). The

atmosphere of Mars as observed by InSight. In *Nature Geoscience* (Vol.

13, Issue 3, pp. 190–198). Nature Portfolio.

<https://doi.org/10.1038/s41561-020-0534-0>

BBC. (2024, October). *Curiosity: Nasa reveals large hole in wheel of its Mars rover*. BBC Newsround.

<https://www.bbc.co.uk/newsround/articles/c4g57kdzglqo>

Chan, C. M., Bai, H. L., & He, D. Q. (2018). Blade shape optimization of the Savonius wind turbine using a genetic algorithm. In *Applied Energy* (Vol. 213). Elsevier BV. <https://doi.org/10.1016/j.apenergy.2018.01.029>

Climate Signals. (2018). *Climate Signals | Surface Wind Speed Change*.

[Climatesignals.org. https://www.climatesignals.org/climate-signals/surface-wind-speed-](https://www.climatesignals.org/climate-signals/surface-wind-speed-change#:~:text=Global%20wind%20trends%20and%20climate,2%5D)

[change#:~:text=Global%20wind%20trends%20and%20climate,2%5D](https://www.climatesignals.org/climate-signals/surface-wind-speed-change#:~:text=Global%20wind%20trends%20and%20climate,2%5D)

Damak, A., Driss, Z., & Abid, M. S. (2013). Experimental investigation of helical Savonius rotor with a twist of 180°. In *Renewable Energy* (Vol. 52, pp. 136–142). Elsevier BV. <https://doi.org/10.1016/j.renene.2012.10.043>

Elachi, C., Wall, S., Allison, M., Anderson, Y., Boehmer, R., Callahan, P., Encrenaz, P., Flamini, E., Franceschetti, G., Gim, Y., Hamilton, G., Hensley, S., Janssen, M., Johnson, W., Kelleher, K., Kirk, R., Lopes, R., Lorenz, R., Lunine, J., & Muhleman, D. (2005). Cassini Radar Views the Surface of Titan. In *Science* (Vol. 308, Issue 5724, pp. 970–974).

American Association for the Advancement of Science.

<https://doi.org/10.1126/science.1109919>

Energy Encyclopedia. (2025). *Types of Wind Turbines - Renewable Energy Sources - Energy Encyclopedia*. [Energyencyclopedia.com](https://www.energyencyclopedia.com).

<https://www.energyencyclopedia.com/en/renewable-energy/wind->

energy/types-of-wind-turbines

ESA. (2015). Huygens's descent to Titan's surface. In *Esa.int*.

[https://www.esa.int/ESA\\_Multimedia/Images/2015/01/Huygens\\_s\\_descent\\_to\\_Titan\\_s\\_surface](https://www.esa.int/ESA_Multimedia/Images/2015/01/Huygens_s_descent_to_Titan_s_surface)

Farozan, I., Fauzi, A., Soetikno, P., & Setyo Indartono, Y. (2025). The Effect of Rotor Aspect Ratio, Stages, and Twist Angle on Savonius Wind Turbine Performance in Low Wind Speeds Environment. In *Results in Engineering* (pp. 104041–104041). Elsevier BV.

<https://doi.org/10.1016/j.rineng.2025.104041>

Johns Hopkins University Applied Physics Laboratory. (2025). *Dragonfly*.

Dragonfly. <https://dragonfly.jhuapl.edu/Why-Titan/>

JPL. (2020). *Mars 2020 Perseverance Launch Press Kit*. NASA/JPL.

[https://www.jpl.nasa.gov/news/press\\_kits/mars\\_2020/launch/mission/spacecraft/power/](https://www.jpl.nasa.gov/news/press_kits/mars_2020/launch/mission/spacecraft/power/)

Kamoji, M. A., Kedare, S. B., & Prabhu, S. V. (2008). Performance tests on helical Savonius rotors. In *Renewable Energy* (Vol. 34, Issue 3, pp. 521–529). Elsevier BV. <https://doi.org/10.1016/j.renene.2008.06.002>

Kavlak, K., & Yongul, A. (2022). Design of Quadruped Mobile Robot with Strandbeest Walking Mechanism to Overcome Concave and Ramp Type Obstacles. In *2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)* (pp. 1–4). <https://doi.org/10.1109/hora55278.2022.9799951>

- Kerikous, E., & Thévenin, D. (2019). Performance Enhancement of a Hydraulic Savonius Turbine by Optimizing Overlap and Gap Ratios. In *ResearchGate*. <https://doi.org/10.1115//GTINDIA2019-2670>
- Landis, G. A., & Oleson, S. R. (2021). Sample Return from Titan. In *ResearchGate*. <https://doi.org/10.3847//25c2cfcb.45d66020>
- Landis, G., Olson, S., Grantier, D., Balkanyi, L., Bur, M., & Krasowski, M. (2019). *NASA Innovative Advanced Concepts (NIAC) Phase 1 Final Report: Venus Landsailer Zephyr*. <https://ntrs.nasa.gov/api/citations/20190034022/downloads/20190034022.pdf>
- Lil, L., Nixon, C., Achterberg, R., Smith, M., Gorius, N., Jiang, X., Conrath, B., Gierasch, P., Simon-Miller, A., Flasar, F., Baines, K., Ingersoll, A., West, R., Vasavada, A., & Ewald, S. (2011). *The Global Energy Balance of Titan*. <https://ntrs.nasa.gov/api/citations/20110023012/downloads/20110023012.pdf>
- Lorenz, R. D. (2017). Wind shear and turbulence on Titan: Huygens analysis. In *Icarus* (Vol. 295, pp. 119–124). Elsevier BV. <https://doi.org/10.1016/j.icarus.2017.06.010>
- Lorenz, R. D., Martínez, G. M., Spiga, A., Vicente-Retortillo, A., Newman, C. E., Murdoch, N., Forget, F., Millour, E., & Pierron, T. (2021). Lander and rover histories of dust accumulation on and removal from solar arrays on Mars. In *Planetary and Space Science* (Vol. 207). Elsevier BV.

<https://doi.org/10.1016/j.pss.2021.105337>

Mao, Z., & Tian, W. (2015). Effect of the blade arc angle on the performance of a Savonius wind turbine. In *Advances in Mechanical Engineering* (Vol. 7, Issue 5). SAGE Publishing. <https://doi.org/10.1177/1687814015584247>

Marinić-Kragić, I., Vučina, D., & Milas, Z. (2022). Robust optimization of Savonius-type wind turbine deflector blades considering wind direction sensitivity and production material decrease. In *Renewable Energy* (Vol. 192, pp. 150–163). Elsevier BV.

<https://doi.org/10.1016/j.renene.2022.04.118>

McQuaide, M., Ellison, D., & Englander, J. (2023). *Dragonfly Phase B Mission Design*. [https://www.researchgate.net/profile/Martin-Ozimek/publication/373256268\\_Dragonfly\\_Phase\\_B\\_Mission\\_Design/links/64e376430acf2e2b52094a79/Dragonfly-Phase-B-Mission-Design.pdf](https://www.researchgate.net/profile/Martin-Ozimek/publication/373256268_Dragonfly_Phase_B_Mission_Design/links/64e376430acf2e2b52094a79/Dragonfly-Phase-B-Mission-Design.pdf)

Mine, V. (2025). *Types of vertical axis wind turbines with rotation principle outline diagram. Labeled educational list with hawt, h-rotor, savonius and darrieus models vector illustration. Power production generator Stock Vector | Adobe Stock*. Adobe Stock.

<https://stock.adobe.com/images/types-of-vertical-axis-wind-turbines-with-rotation-principle-outline-diagram-labeled-educational-list-with-hawt-h-rotor-savonius-and-darrieus-models-vector-illustration-power-production-generator/587091109>

Mohsenizadeh, M., & Zhou, J. (2015). Kinematic Analysis and Simulation of Theo Jansen Mechanism. In *ResearchGate*.

[https://www.researchgate.net/publication/322144907\\_Kinematic\\_Analysis\\_and\\_Simulation\\_of\\_Theo\\_Jansen\\_Mechanism](https://www.researchgate.net/publication/322144907_Kinematic_Analysis_and_Simulation_of_Theo_Jansen_Mechanism)

NASA. (2017, December 5). *Opportunity*. NASA Science.

<https://science.nasa.gov/mission/mer-opportunity/>

NASA. (2018, May 2). *Titan: Facts*. NASA Science.

<https://science.nasa.gov/saturn/moons/titan/facts/>

NASA. (2020). *Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)*.

[https://mars.nasa.gov/internal\\_resources/788/](https://mars.nasa.gov/internal_resources/788/)

Patnaik, L., & Umanand, L. (2016). Kinematics and dynamics of Jansen leg mechanism: A bond graph approach. In *ResearchGate*.

<https://doi.org/10.1016//j.simpat.2015.10.003>

Punde, Y., Dhande, Y., Chopde, A., & Bagade, S. (2020). *Design and Linkage Analysis of Theo Jansen Mechanism*.

<https://www.ijert.org/research/design-and-linkage-analysis-of-theo-jansen-mechanism-IJERTV9IS090170.pdf>

Saha, U. K., Thotla, S., & Maity, D. (2008). Optimum design configuration of Savonius rotor through wind tunnel experiments. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(8-9), 1359–1375.

<https://doi.org/10.1016/j.jweia.2008.03.005>

Sauder, J., Hilgemann, E., Johnson, M., Parness, A., Bienstock, B., Additional, J., Kawata, J., & Stack, K. (2017). *Automaton Rover for Extreme Environments NASA Innovative Advanced Concepts (NIAC) Phase I*

- Final Report Principle Investigator*. [https://www.nasa.gov/wp-content/uploads/2016/04/niac\\_2016\\_phasei\\_saunders\\_aree\\_tagged.pdf](https://www.nasa.gov/wp-content/uploads/2016/04/niac_2016_phasei_saunders_aree_tagged.pdf)
- Schmitz, P. (2020). *A Comparison of Radioisotope and Solar Array/Battery Power Systems in the Solar System*.  
<https://ntrs.nasa.gov/api/citations/20220002310/downloads/E-20019P-Final%20Schmitz%20Paper.pdf>
- Sengupta, S., & Bhatia, P. (2017). Study of Applications of Jansen's Mechanism in Robot. *International Journal of Advance Research and Innovation*, 5(3), 92–98. <https://doi.org/10.51976/ijari.531716>
- SKYbrary. (2020). *International Standard Atmosphere (ISA) | SKYbrary Aviation Safety*. Skybrary.aero. <https://skybrary.aero/articles/international-standard-atmosphere-isa>
- Sobczak, K. (2018). Radware Bot Manager Captcha. In *Iop.org*.  
<https://iopscience.iop.org/article/10.1088/1742-6596/1101/1/012034/pdf>
- Spaceflight Now. (2025). *Atlas 5 rocket runs through practice countdown before Mars rover launch – Spaceflight Now*. Spaceflightnow.com.  
<https://spaceflightnow.com/2020/06/22/atlas-5-rocket-runs-through-practice-countdown-before-mars-rover-launch/>
- Strandbeest. (2025). *Strandbeest*. Strandbeest.com.  
<https://www.strandbeest.com/>
- Swan, C. (2008, August 6). *Dynamic Pressure*. Begellhouse EBooks.  
[https://doi.org/10.1615/atoz.d.dynamic\\_pressure](https://doi.org/10.1615/atoz.d.dynamic_pressure)

- Taylor, F. W., Svedhem, H., & Head, J. W. (2018). Venus: The Atmosphere, Climate, Surface, Interior and Near-Space Environment of an Earth-Like Planet. In *Space Science Reviews* (Vol. 214, Issue 1). Springer Science+Business Media. <https://doi.org/10.1007/s11214-018-0467-8>
- The Planetary Society. (2020). *Cost of Perseverance*. The Planetary Society. <https://www.planetary.org/space-policy/cost-of-perseverance>
- Tumbleweed Mars. (2024, July 7). *Our Rover - Team Tumbleweed*. Team Tumbleweed. <https://www.teamtumbleweed.eu/our-rover/>
- Zarnecki, J. C., Leese, M. R., Hathi, B., Ball, A. J., Hagermann, A., Towner, M. C., Lorenz, R. D., McDonnell, A. M., Green, S. F., Patel, M. R., Ringrose, T. J., Rosenberg, P. D., Atkinson, K. R., Paton, M. D., Banaszkiewicz, M., Clark, B. C., Ferri, F., Fulchignoni, M., Nadeem, J., & Kargl, G. (2005). A soft solid surface on Titan as revealed by the Huygens Surface Science Package. In *Nature* (Vol. 438, Issue 7069, pp. 792–795). Nature Portfolio. <https://doi.org/10.1038/nature04211>

# Appendices

## Appendix A Ethical approval letter



29 March 2025

Dear Mr Kurian ,

Reference: CURES/24701/2025

Project ID: 28127

Title: A Rover Locomotion Mechanism Powered by Natural Energy

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

1) Your supervisor has requested that you apply for approval through CURES because:

- The journals or data are in a sensitive area (please discuss this with your supervisor)
- The project will be embargoed i.e. **will not be publicly available via the Cranfield library immediately or longer term**

2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

**Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.**

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

## Appendix B Further Robot Videos and Pictures

The following QR code and link lead to a PowerPoint presentation containing video highlights of the WANDER-Bot design, development, and prototyping process. It shows the construction, experimental testing, and showcases the ability of the robot to walk forward in omni-directional winds, meeting the project aim.



[SK IRP WANDER-Bot Video Highlights.pptx](#)

[https://cranfield.sharepoint.com/:p:/s/SamKurian-MScIRP2025-UGT-FEAS/EcYcFYoOuUdEotW1BCQbk1gBNVpEjuR2Uu7L6f3\\_IG7R1w?e=Bna4SE](https://cranfield.sharepoint.com/:p:/s/SamKurian-MScIRP2025-UGT-FEAS/EcYcFYoOuUdEotW1BCQbk1gBNVpEjuR2Uu7L6f3_IG7R1w?e=Bna4SE)

This presentation link is accessible as 'Read-only' to all members at Cranfield.

If you have any issues accessing the document, please contact Sam Kurian

[sam.kurian@cranfield.ac.uk](mailto:sam.kurian@cranfield.ac.uk)