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WIND-POWERED LOCOMOTION MECHANISM FOR A WANDERING ROBOT EXPLORING TITAN

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1 ABSTRACT

This paper proposes a wind-powered locomotion mechanism design for wandering robots on Titan, WANDER-Bot. Existing planetary robots use a substantial amount of their power budget for locomotion. Typical power sources include RTGs and solar cells, which experience performance degradation in their power output over time, and are not suitable for replacement or repair. Composed of a Savonius wind turbine mechanism, reduction gearbox mechanism, and Jansen linkage walking mechanism, the proposed wandering robot locomotion design addresses these limitations by using wind energy, and simple mechanical links designed with consideration of ISRU manufacturing. The WANDER-Bot lab prototype takes a low-cost, low-storage, low-power approach to the design and locomotion. Performance analysis is conducted on the robot components in replicated Titan conditions.

Keywords: Jansen mechanism, Titan, Planetary exploration, Savonius wind turbine, low-cost, ISRU.

2 INTRODUCTION

At the forefront of space exploration, planetary robotic missions have opened our understanding of different worlds beyond Earth, enabling us to better understand the transformation of landscapes, terrain, and atmospheric conditions. They are one of our greatest assets in our search for life and its origins.

Previous and current robotic missions have used RTGs and solar cells as their means of generating power, primarily for wheeled locomotion. Both power sources experience degradation over time, only able to generate nominal power at the start of the mission. Thus, as the mission progresses, the power budget for locomotion declines, decreasing the range that the robot can travel from its landing site with each passing year. These systems are also expensive to develop and operate, and consume a substantial amount of the robot's volume and mass budget, which is particularly important when considering the launch vehicle.

To address this in the future, developing robot designs which allows on-site fabrication and ISRU operation compatibility reduces the storage requirement for transportation of the robot to its destination. Using simplified mechanical links and components for the locomotion design increases robustness in hostile environments, while reducing development costs, and allows on-site maintenance and repair. Powering locomotion mechanisms directly using natural energy sources such as wind offsets the power demand for locomotion, enabling the system to operate indefinitely. This would allow the power budget which would typically be allocated for locomotion to be used for other robot electrical systems, prolonging mission end-of-life.

This paper proposes an early design concept for a wind-powered locomotion solution for exploration on Titan, WANDER-Bot (Wind Actuated Navigator, Discoverer, Explorer and Research Robot). The integrated system will be composed of three main constituent parts: a wind energy capture mechanism using an omnidirectional Savonius vertical wind turbine, a reduction gearing mechanism for torque amplification, and a Jansen-inspired walking mechanism for legged locomotion. The robot will use simplified mechanical links and interface designs for easy, low-cost manufacturing and maintenance. Using this approach also allows multiple robots to be manufactured for a low-cost, fast-exploring robot swarm.

The robot will be designed for 3D printed prototyping in the lab, making it inherently compatible with future on-site ISRU additive manufacturing methods. The robot is expected to self-start and wander forward regardless of the wind direction.

3 THE ENVIRONMENT OF TITAN

While applicable to multiple planetary bodies with wind and firm surface terrain, the application of this locomotion solution was for exploration on Titan. The largest moon of Saturn and around 1.4 billion km from the Sun, Titan holds a very high scientific value and is the target for many future exploration missions, such as Dragonfly. It has several striking similarities with Earth, namely being the only other known body in the solar system to possess stable liquids on its surface. With a nitrogen-rich atmosphere much denser than Earth's, this moon has a plentiful presence of methane and other hydrocarbon compounds: the building blocks of life. It also has similar geological features, such as dunes, valleys, cryovolcanoes, and weather cycles. Its thick atmosphere shields the surface from most of the harmful radiation. Combined, these factors make the body a viable candidate to potentially support life which function based on hydrocarbon processes. [1].

The most prominent past missions to Titan include the Voyager 1 flyby in 1980 which gave us the first close up look at Titan [1]. It revealed the dense Nitrogen-rich atmosphere and thick haze that obscured the surface [2]. The Cassini-Huygens probe in 2005 is the only landing to date on its surface. During its descent and landing, the probe revealed its Earth-like terrain features, shown in Fig. 1, its atmospheric conditions, and its molecular composition [2]. 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 [1].

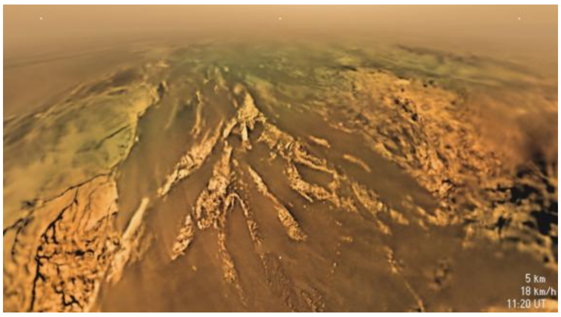

Figure 1 The surface of Titan, captured by Huygens probe (ESA, 2015)

Based on data returned from Huygens and other missions, Tab. 1 shows some of the environmental conditions at Titan's surface.

Table 1 Environmental conditions Titan [1][4][5][6][7]

Parameter name	**Titan value**
Surface Pressure	1470 mbar
Atmospheric Density	5.3 kg m^{-3}
Surface Wind Speed	<1 m s^{-1} typical
Gravitational Field Strength	1.352 m s^{-2}
Solar Irradiance	15.2 W m^{-2}
Surface Terrain	Frozen plains, dunes, lakes of methane

The dynamic pressure expected on Titan's surface can be calculated using:

$$q = \frac{1}{2} \times \rho \times v^2 \qquad (1)$$

Using the density and typical windspeed on Titan, the dynamic pressure on the surface can be calculated as 2.715 Pa. From this, using Earth's sea level atmospheric density of 1.225 kg m^{-3}, the equivalent windspeed can be calculated as 2.105 ms^{-1} to simulate the dynamic pressure on Titan, which can be felt as a very light breeze.

4 ROBOT CONCEPT DESIGN

4.1 The Jansen Walking Mechanism Design and Motion Simulation

Invented by Dutch Artist Theo Jansen, the Jansen linkage is a means of converting rotary motion of a crankshaft into linear forward movement through legged locomotion [8]. It only has a single degree of freedom and is composed of 13 separate link elements with ratios which are well-established in literature, as shown in Fig. 2 [9]. These relative ratios define the walking gait of the foot. In 1990, Jansen developed a program to optimise these link ratios; the outcome was a foot profile which had an asymmetrical mound shape and a flat base, which delivered the forward drive [10]. This profile delivered a stable walking motion, keeping the assembly frame parallel to the ground.

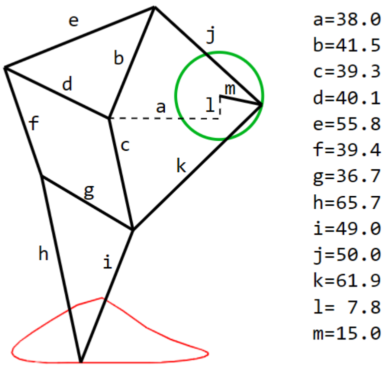

Figure 2 Jansen linkage ratios [9]

Since then, Jansen built kinetic wind-driven sculptures, known as Strandbeest. It uses the Jansen mechanism, and is powered using wind sails. Strandbeest has three pairs of legs on each side, each pair rotating in-phase, offset by an angle of 120°. This allows maximum stability of the robot, as it means that at any given instance, there is always one leg in the flat portion of the walking profile in each corner, assuming a supporting stance and taking the weight load of the robot [10]. The pure mechanical nature of Strandbeest demonstrates its resilience in the harsh marine saltwater environment, against temperature changes, rough weather events, and abrasive degradation from the sand. However, one limitation with the Strandbeest design is that to date, its sail-driven nature means that it can only walk forward when the wind is blowing behind it in favour of its walking direction [8].

WANDER-Bot applies the Jansen locomotion mechanism for its legged locomotion, similar to its application in Strandbeest. Developing the system required several iterations of the legged system design, starting with a scaled down single leg to assess feasibility of manufacture. All iterations used bearings at the pivots to minimise resistance.

Motion simulations of the leg were created to verify the profile characteristics drawn by the foot with literature, and assess the accuracy of the leg prototype walking gait. The design was then optimised for 3D printing, by eliminating support material and adhesive by using interference-fit joins. The success of this meant that the design could be upscaled for larger leg assemblies, first as leg pair modules, then as the entire robot Jansen mechanism assembly. Throughout its development, iterative improvements were made to remove resistance by reducing weight, and increase lateral stability by redesigning joins. Upon experimentally testing the leg pair prototype, it was found that the foot traced the expected motion profile of the Jansen walking gait, as shown in Fig. 3.

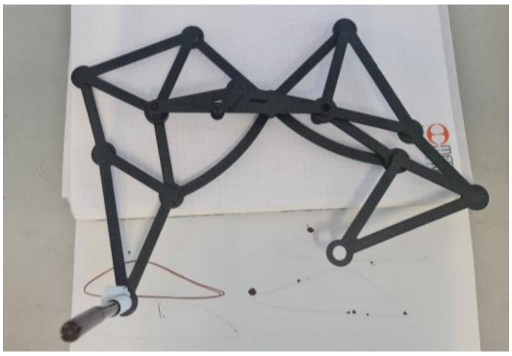

Figure 3 Experimental Jansen mechanism walking gait

However, it was observed that there were instances of increased resistance to rotate each cycle, due to leg ‘lock-up’. This happened when the angles between links were near straight, reducing the effect of the lever arm between the pivots. This also occurred when the leg underwent sudden changes in direction and speed, leading to inertia in the bearings. Another point was when the entire weight of the leg was suspended by the crankshaft and mechanical arm, meaning that all the mechanical work was going into raising the mechanism to its state of maximum potential energy. The observed positions of maximum rotational resistance are shown on the motion simulation Fig. 4.

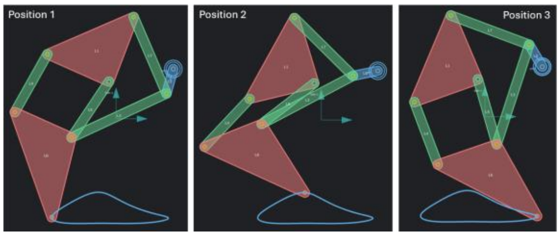

Figure 4 Motion simulated Jansen leg configurations at each resistance maximum

With all the Jansen linkages assembled, the complete leg mechanism is shown in Fig. 5.

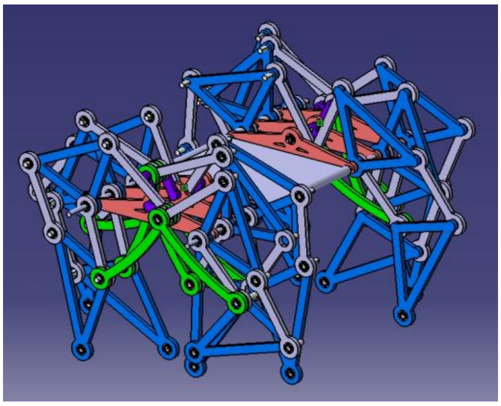

Figure 5 Full Jansen mechanism locomotion assembly model for WANDER-Bot

4.2 Savonius Turbine Wind Energy Capture Mechanism

With the legged mechanism designed, the next step was to design the wind energy capture mechanism. This system had to be omnidirectionally operating to move the robot forwards regardless of wind gust direction. This ruled out the sail design used in Strandbeest, and all horizontal axis wind turbines, despite their higher efficiency. Of all the omnidirectional vertical axis wind turbine candidates, the Savonius drag-type turbine was selected, due to its high torque production and self-start capability at low wind speeds, and simple-to-manufacture design.

Design features of this turbine were further optimised to enhance performance. The final design had an elliptical blade cross-section with an eccentricity of 0.6, as opposed to the typical semi-circular cross section. This increased the drag coefficient differential between the advancing and returning blades, improving torque. It also had a dual helical blade design with 180^0 twist; this created a more uniform torque throughout each blade revolution without buffeting. An additional benefit was an improvement to the self-start ability of the turbine in any position facing the oncoming airflow. End plates were added to reduce tip losses and improve efficiency.

This was the third iteration of the turbine design for WANDER-Bot; previous designs had opted for shaftless blades, and considered additional blade features such as blade overlap ratio, gap ratio, and blade arc angle. However, these were phased out in favour of build quality when being 3D printed. The layer-by-layer approach of additive manufacturing meant that the ratios of these features were not being preserved further up the turbine, leading to poor build quality and losses in efficiency.

Experimental tests of the turbine prototypes at different windspeeds showed that turbine 3 consistently demonstrated the highest RPM, as shown in Fig. 6. As it possessed the largest diameter, it also meant that it was generating the highest mechanical torque. Combined, these findings meant that turbine 3 was generating the most mechanical work to power the locomotion mechanism cycles for a given windspeed, making it the ideal candidate for the WANDER-Bot integrated system.

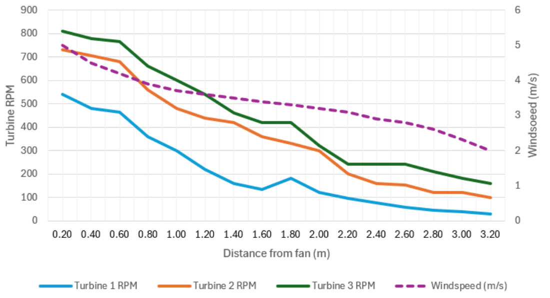

Figure 6 Graph showing RPM of each turbine design at different distances from fan and windspeeds

4.3 Gearing Design

The final design for this robot opted for a 16:1 reduction gearing mechanism, increased from the initial 8:1 reduction. With this, preliminary tests demonstrate the capability of the robot to self-start and walk forward in omnidirectional winds. For every 16 full rotations of the turbine, the Jansen locomotion mechanism completes one full cycle. Only simple gear designs have been used, such as lightened spur and bevel gears. WANDER-Bot reduces gear engagements as much as possible, to minimise friction and rotation resistance for each cycle.

4.4 Integrated System Design

The integrated system brings together the 3 aforementioned constituents, to create the simple WANDER-Bot mechanical robot locomotion assembly, manufactured primarily with 3D printing. Its simple mechanical connections make it easy to build in a short period of time, easy to maintain, and easy to repair in the event of components being damaged. The complete WANDER-Bot integrated system can be seen in Fig. 7.

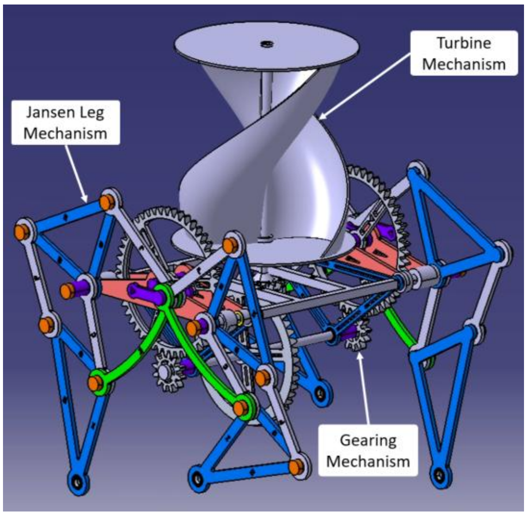

Figure 7 WANDER-Bot integrated system CAD model

5 PROTOTYPE AND TESTING

Early tests of the prototype demonstrate the ability of the robot to self-start and walk forward, with stability, in omnidirectional winds. Simulating the 14% weight requirement of Titan, the robot shows ability to self-start and begin walking at even lower windspeed thresholds. The test campaign and final WANDER-Bot prototype can be seen in Fig. 8 and Fig. 9.

Figure 8 Experimental set-up for integrated robot testing

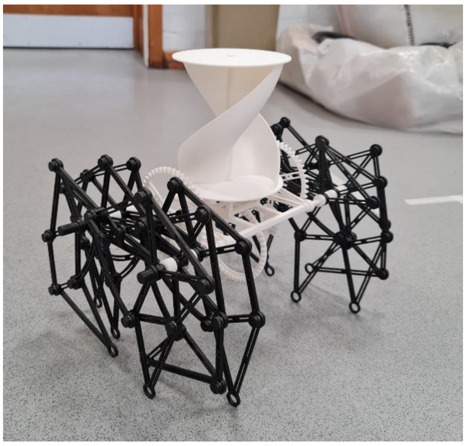

Figure 9 WANDER-Bot testing prototype

6 CONCLUSION AND FUTURE WORK

The proposed design concept and prototype demonstrates the feasibility of a low-cost, low-power, low-storage mechanical locomotion solution, using natural wind energy to power a Jansen mechanism-based robot. Preliminary testing of WANDER-Bot shows that it is able to walk forward in omnidirectional winds. Still in its design infancy, further work is required to mature the design of the wandering robot. This includes improving its capability to self-start at lower windspeeds, introducing steering mechanisms, introducing variable ratio gearing with a motorised gearbox to control speed and torque, and introducing basic robot perception and autonomy for future navigation, path planning, and obstacle avoidance.

7 ACKNOWLEDGEMENTS

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