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Wheeled Rovers With Posable Hubs for Terrestrial and Extraterrestrial Exploration

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ABSTRACT Space exploration and work such as search and rescue or resource mining is dangerous and often unsuited to manned platforms due to the associated dangers and costs. As a result unmanned wheeled rovers dominate the sectors as they exhibit a lower cost of transport to other legged systems. However, wheels have limited debogging and self-recovery ability if they become stuck. We propose a Posable Hub, where using electric linear actuators instead of a rigid spoke structure, the wheel centre hub can be actively manipulated. We construct a four wheeled rover with Posable Hubs and perform experiments on debogging, chassis levelling for sloped and uneven terrains and generating locomotion with a failed drive motor by converting gravitational potential energy into rotational motion. Our experiments compare the results to classical wheels and validate the superiority of our Posable Hubs for extreme and unstructured terrains such as environments experienced in terrestrial and extraterrestrial exploration.

INDEX TERMS Extraterrestrial exploration, extreme environments, roving vehicles, wheeled robots.

I. INTRODUCTION

Unmanned robotic platforms are often utilised for applications where a human life may be put in danger, or development and monetary costs are too significant for a manned platform. Common applications for such rovers include urban and non-urban search and rescue [1], [2], disaster relief [3], various mining [4] and most evidently extraterrestrial applications [5].

With the increased interest and ability brought on by technological advances, human kind is more engaged than ever in exploring planetary bodies, moons and asteroids, as well as establishing a permanent base on nearby planets [6]. With this exploration comes a push for more effective and robust locomotion systems that can overcome extreme, unpredictable and unstructured terrain.

As a locomotion system's efficiency is highly dependant on the contact it makes with the ground [7], wheels continue to be the locomotion method of choice for platforms designed for these operational environments. Wheels coupled with a suspension system allow desired operation to be maintained [8], as these mechanisms protect the vehicle from mechanical vibrations, prolonging the robot's operational life [9].

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However, these systems present certain and unique disadvantages, such as higher launch volume requirements, when compared to a platform with no, or in-wheel suspension, and limited obstacle clearing abilities and slip [10]. A further significant drawback is their lack of debogging ability, as seen with NASA's Spirit rover ceasing operations after becoming stuck in a sand trap, unable to recover [11]. Further, no current wheeled systems allow for chassis pose selection, and very few systems offer redundancy upon motor failure.

Our research proposes a Posable Hub for travel over unstructured terrain. Such a system allows small robots to travel in rough terrain by adjusting the robot pose while not affecting the physical size of the overall wheel, and maintaining a close efficiency to that of classical wheels. Our system further offers the ability to generate locomotion from gravity, should a drive motor fail. We demonstrate the superiority of our wheel in sloped environment traversal, and its debogging ability by allowing the rover to actively manipulate its wheelbase. A rover using our wheels is shown in Fig. 1.

II. RELATED WORK

Robots designed for unstructured terrain traversal usually fall into one of two categories, wheeled and legged systems. Most common systems seen in the field are robots utilising conventional wheels with suspension systems, due to their

FIGURE 1. A rover utilising four Posable Hubs. The ride height of one wheel is manipulated to show its ability to climb an obstacle while maintaining a level chassis and ground contact with all four wheels.

simplicity and low Cost of Transport (COT). These systems often present certain mobility limitations and hence legged robots, with high numbers of degrees of freedom and superior obstacle clearing abilities are then used. However, legged platforms are of higher mechanical, electrical and control complexity and result in a higher COT.

Most applications of these systems focus on unstructured terrains for terrestrial and extraterrestrial applications, as unstructured terrain can be found all over the solar system. We review systems with abilities to perform space exploration as well as terrestrial applications as our proposed system is well suited for both types of uses.

A. WHEELED PLATFORMS

A wheeled locomotion platform most fundamentally consists of a wheel, suspension unit and a drive unit. A variety of system configurations are commonly used in the robotics field and exact configuration generally depends on the application. These systems are designed for specific uses as important design considerations have to be considered to suite an specific, predetermined application.

Most commonly utilised systems for terrestrial robotics are a double wishbone [12] and Rocker-Bogie [13] suspension. As this system is mounted outside of the wheel it adds to the size of the wheeled system. This outside mounting allows the wheel to have high vertical travel, which directly contributes to the size of obstacles the system can overcome while maintaining surface contact. This is very effective at providing continuous wheel traction over varied terrain [14].

Further, Rocker-Bogie suspension is most commonly used for extraterrestrial rovers and consists of three wheels fixed to two geometric arms that are secured to the vehicle via pivot points [15]. This configuration provides a passive system with an exceptional ground clearance and the ability to drive over obstacles that are as tall as a single wheel [16]. When an obstacle is encountered, the pivot arms allow the leading wheel to translate its forward motion into an upward motion and effectively climb over the obstacle, much taller than the wheel's height. Most notable example of this system used in the field is NASA's extraterrestrial rovers [17].

Configurable wheels and whegs have been proposed and combine desired properties from both wheeled and legged systems to create an alternative design for robotic platforms [18]. In doing so they can be designed for specific use cases and therefore optimised for desired performance properties such as size, weight and shape [19]. The whegs can transform from a round wheel to a leg-like system, significantly increasing their ability to overcome obstacles. Cockroach inspired whegs can climb obstacles of 175% their height [20], and others passively geared whegs up to 240% their height [21].

B. LEGGED PLATFORMS

Other emerging approaches to locomotion over unstructured terrain are legged systems. Legged systems such as Bipeds [22], Quadrupeds [23], [23], Hexapods [24] and other variants are able to navigate such terrain due to their extra degrees of freedom, when compared to a wheel. This allows for greater obstacles to be overcome for similarly sized systems, of wheeled or tracked equivalence.

Legged systems attract uses from robotics for significant off-road uses, due to their exceptional mobility as systems with higher degree of freedoms provide better ability to traverse the surface [25]. However, this significant benefit requires complex control, accurate forward perception and proves inefficient from the perspective of power consumption and time, compared to wheels and tracks. As a results of the COT of legged robotic being significantly higher than wheels, wheels and suspension systems tend to see higher use on exploration rovers.

C. OUR WORK - POSABLE HUB

Our work focuses on extending the ability of wheels, while maintaining a relatively low COT. We propose, design, test and validate a wheel with a movable centre hub. This results in increased degrees of freedom from a traditional wheel, yet limits the power consumption when compared to a leg.

We focus on overcoming obstacles and maintaining a posable chassis for sensitive payloads, as legs are able to achieve. When the extra degrees of freedom, and possibility of the chassis, are not needed, our wheel is passive and consumes no more power than a traditional wheel. This allows for the COT and obstacle-clearing ability to be dynamically chose and adjusted based on the specific operational requirements.

Our system also remains self contained, with all the components located within a wheel. Doing this limits the required storage and operational volume and is significantly lower than a Rocker-Bogie or double wishbone system. The low volume proves beneficial for extraterrestrial applications as the required launch volume can be minimised.

III. SYSTEM DESCRIPTION

A. POSABLE HUBS

The Posable Hubs used in the rover construction are originally proposed in [26], [27] and adapted for linear actuators in [28]. The wheels have three Degrees of Actuation (controllable Degrees Of Freedom) in x, y and *yaw* in centre hubs plane, where y is parallel to the force of gravity and x therefore parallel to the chassis. The *yaw* rotation of the centre hub is kinematically restricted as it co-rotates with the axle to

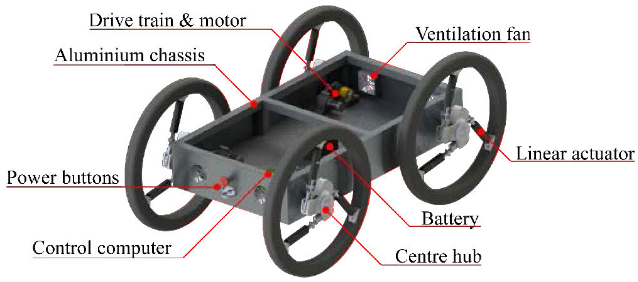

FIGURE 2. Computer rendering of the chassis and annotated with the major components.

transfer rotational energy to the outer rim. Motion in y and x is controlled via the three electronic linear actuators mounted to the outer rim and centre hub.

These actuators can be locked in any position, to maintain the low Cost of Transport of traditional wheels. Upon operational requirements the actuators move the centre hub within its workspace as desired to exhibit capabilities not seen on traditional wheels. The wheels are constructed from rigid aluminium and pneumatic rubber tires with a diameter of 600mm. These wheels have a maximum static loading of 600N and maximum dynamic loading of 75N. The actuators used are Actuonix T16 Micro Linear Actuator and make use of a worm drive achieving a maximum stroke velocity of $46mm^{-s}$.

B. ROVER CHASSIS

The rover chassis was constructed from aluminium sheets and square profiles to optimise the strength-to-weight ratio. The chassis measures 1000×600mm with an 800mm wheelbase. Components such as motor mounts and axles bearings are mounted directly to the frame to maintain rigid structure. The chassis houses an internal payload area of $0.035m^3$ to accommodate any further system upgrades or generally payload. The chassis is also capable of carrying external payloads mounted on top of its aluminium skin. The rectangular construction allows for easy component mounting and replacement/upgrades should they be necessary. This is a prototype chassis and was designed for ease of construction and testing, one for a specific application can be designed to optimise certain operational requirement such as an increased payload bay.

1) MOTORS AND DRIVE TRAIN

Each wheel is individually driven by a DC motor via a high torque gearbox. The motors used are rated for 63rpm and 1.76 N.m of torque. Each motor is mounted firmly to the chassis and is connected to the axle via a timing belt with a further 3:1 reduction. The resultant toque on the axle is therefore 5.28 N.m and max wheel rpm is 21.

The motors and the drive trains are mounted firmly to the chassis, however the timing belt is removable. This was designed to allow decoupling between the motor and the axle for simple conversion from a driven axle to a free turning axle. This was required for generation of motorless motion, explained in Section V-C.

TABLE 1. Table showing each component weight and overall rover weight.

Component	Weight (kg)
Chassis	8.75
Wheel with actuators	2.58
Motor	0.66
Drive train	0.45
Battery	2.20
Total rover weight[1]	28.84

The motors are controlled via a 17A peak motor controller that receives PWM from the onboard controller. The current of each motor is read by the controller, and fused to ensure safe operating limits are maintained.

2) ELECTRICAL POWER SYSTEM

The electrical power system for the rover is contained on a single printed circuit board (PCB). The PCB encloses the motor controllers for the main drive motors, voltage converters and fuses for further power distribution. The main power comes from an onboard battery, that is distributed to the motor controllers and wheels via the PCB. Each wheel then has further motor controllers enclosed within that power the linear actuators for hub control. The Arduino microcontrollers are powered by the battery and step down the voltage to the required level for data recording sensors. A main power switch and a safety push switch are installed that can cut power should it be necessary.

3) COMPONENT WEIGHTS

The weight of all the components was important and considered during the design process. An emphasis was put on keeping the rover lightweight, in order to minimise the load on the wheel actuators and minimise the power usage. Each component was chosen with consideration of other components, to ensure everything works together as a complete system. Table 1 lists the individual weight of each component, and the overall weight of the system. This weight is used for the Cost of Transport calculations in later sections of this article.

C. SOFTWARE AND CONTROL FRAMEWORK

The rover has an onboard microprocessor, an Arduino Mega. This unit acts as a master controller that takes in input from a joystick, and other onboard sensors to record data. The master also processes the ride height, and chassis horizontal offset positions, and communicates this to each wheel.

Each wheel has an Arduino Nano built in as a slave, that performs the necessary kinematics to determine the position of each of its three linear actuators, based on the ride height and horizontal offset position it receives from the master. The slave also controls each motor controller that in turn controls each linear actuator, and reads the actuator positional feedback from a potentiometer. A PID controller is used to control the actuator positions. Both the master and the slave are programmed in C and use I2C and Serial as the communication protocols to communicate amongst each other.

1) DATA COLLECTION AND PROCESSING

The data was collected using on board current sensors, Inertial Measurement Unit (IMU) and encoders. At the beginning

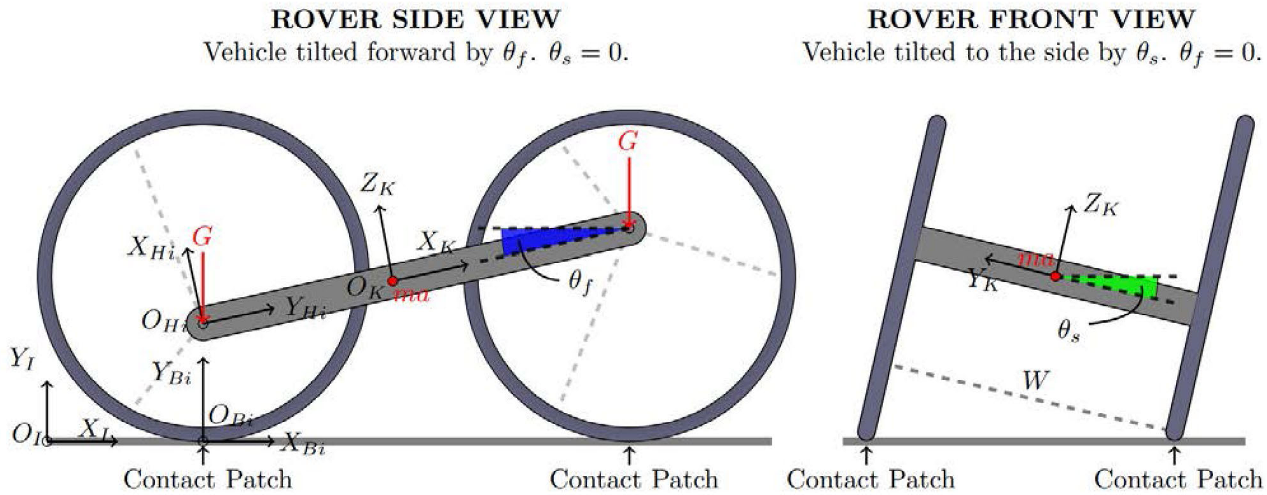

FIGURE 3. Schematic view of the rover showing side (left) and front (right) view of the rover with annotated coordinate frames. θ_f shows the forward tilt of the chassis while θ_s shows the side tilt from the horizontal plane (perpendicular to gravity). G denotes the points at which the gravitational force is transferred from the chassis to the wheels through the centre hub.

of each control loop, all the data was collected and recorded onto an SD card. The current sensor was placed at the input connection of the battery to the power distribution board.

The IMU was mounted to the centre of the chassis and recorded the acceleration and gyroscopic data in roll, pitch and yaw. Wheel rotations were recorded using a quadrature encoder with an accuracy of 2400 tics per rotation. This rotational position was then used to control the wheel centre offset to maintain the set ride height, and also to record the rotational data of the wheels. The data was processed and smoothed in MATLAB, as well as analysed and plotted.

IV. MODELLING AND FUNCTIONALITY

A. FRAMES OF REFERENCE

Frames of reference used for the description of this platform in kinematics begin with an inertial world frame F_I with all others enclosed within. Each wheel has a body frame F_B that is attached to the internal radius of the wheel rim, and co-rotates with the wheel. The axle mounting of each wheel has a hub F_H reference frame attached to the centre of rotation, and co-rotates with the wheel. As the origin of F_H (O_H) is also permanently fixed to the axle, it can be used to describe the rotational[2] centre of each wheel, and also the permanent axle mounting position on the extremities of the chassis. To describe the chassis position in F_I, a reference frame F_K is attached to the centre of the chassis. These reference frames and associated measurements are illustrated in 3.

B. BODY POSE LIMITS

Fig. 3 (left) shows the rover body forward tilt and 3 (right) shows side to side tilt. Maximum tilt about forward X_K (θ_f) and side Z_K (θ_s) directions is calculated using

$$\theta_{imax} = tan^{-1}\frac{\Delta r_{max}}{D_{A-A}} + \pi n \quad n \in \mathbb{Z} \tag{1}$$

[2]For clarity, this means the effective centre of the wheel after actuator movement, not the geometric centre of the wheel.

where Δr_{max} is the maximum achievable manipulated radius offset and D_{A-A} is the axle-to-axle distance of the wheelbase. Once the θ_{imax} is know, θ_i value is given by

$$-\theta_{imax} \leq \theta_i \leq \theta_{imax}, \tag{2}$$

where θ_i is either θ_f or θ_s. θ_{fmax} in X_K direction, and θ_{smax} in Z_K were calculated for our specific platform and are 3.563° and 4.731° respectively. θ_f and θ_s range is then determined by Equation 2

$$-3.563° \leq \theta_f \leq 3.563°, \tag{3}$$

$$-4.731° \leq \theta_s \leq 4.731°. \tag{4}$$

ride height envelopes are given by Normal Ride Height ± | max actuation | for our platform that is min 251.5mm and max of 351.5mm

C. WHEEL RIDE HEIGHT CONTROL ON SLOPES

Each wheel has the ability to adjust its ride height independently of other wheels. This mean that the distance between point O_H in B_Y and a flat horizontal terrain can be manipulated and actively set. This is useful for precisely controlling the tilt of the chassis on uneven terrain such as slopes. We can calculate the ride height of ith wheel using

$$RH_i = RH_N + \Delta RH_i, \tag{5}$$

where RH_N is the nominal ride height of the wheel and ΔRH_i is dependant on RH_i position in Z_K and given by

$$RH_i = \begin{cases} Wtan(\theta), & \text{if } i_z > 0 \text{ in } Z_K \\ -Wtan(\theta), & \text{if } i_z < 0 \text{ in } Z_K \\ 0, & \text{if } i_z = 0 \text{ in } Z_K \end{cases} \tag{6}$$

where W is the width of the chassis and θ is either θ_s or θ_f to denote the tilt angle and direction, as show in Fig. 3.

D. COST OF TRANSPORT

Cost of Transport (COT) is used to calculate the efficiency of a transportation system. It is a dimensionless measure, and as a result allows comparison between a wide variety of locomotion systems such as walking, swimming and driving. It is useful for the evaluation of this system as we can calculate COT of the system when actuated, and obtain the base data for comparison of our system to the traditional wheel and DC motor.

COT is calculated via one of two ways using

$$COT \triangleq \frac{E}{mgd} = \frac{P}{mgv}, \tag{7}$$

where E is energy used to move the system with mass m a distance of d, under standard gravity g. Or, the energy P used to move the system at a constant velocity v, under standard gravity g.

E. ROVER FUNCTIONALITY

This rover has various functionalities not seen on traditional rovers, the major functions are explained below.

1) RIDE HEIGHT ADJUSTMENT

The ride height of the rover is determined by the wheel radius and the chassis height from the axle. The normal ride height of the chassis is 230*mm*, and with adjustment of the centre hub, the effective ride height changes with the effective radius in the range of 230 ± 50 *mm*.

2) BODY LEVELLING

By manipulating the ride height of each wheel whilst in motion on uneven terrain, each wheel acts as its own suspension system, adjusting its ride height to compensate for the uneven terrain. In doing so each wheel maintains the required ride height to keep the chassis level. This technique can be used to maintain a level chassis while traversing uneven terrain.

3) SLOPE TRAVERSAL

Similarly to body levelling on uneven terrain, the same technique can be used to maintain a level chassis when driving on an incline and experiencing sideways chassis tilt. Further, if driving along the gradient of an incline, each wheel can be adjusted to maintain optimal Centre of Gravity (COG) and increasing rover stability by lowering the COG, or by shifting it uphill. The maximum slope able to mitigate through body levelling is determined by the wheel workspace and the chassis geometry, and can be calculated as outline in Section IV-B.

4) WHEELBASE ADJUSTMENT

The wheelbase of the rover is determined by the spacing of its axles which always remain fixed to the chassis. However, the Posable Hubs can change their centre of rotation and rotate about a different point the their geometric centre. This allows for the effective wheelbase of the rover to be manipulated.

The geometric wheelbase for this rover is 800*mm*, axle-to-axle. However the Posable Hub allows for 100*mm* of manipulation [26] due to the workspace of the wheel, therefore the effective wheelbase is 800 ± 100 *mm*.

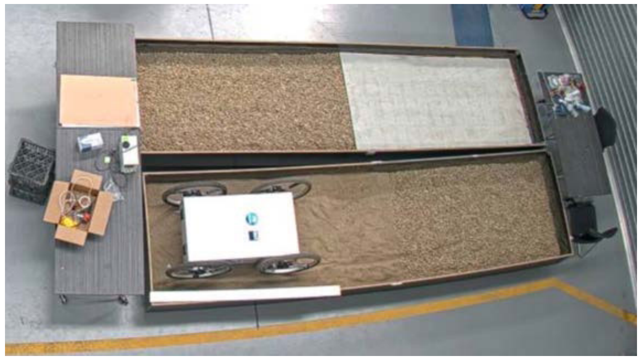

FIGURE 4. Two terrain boxes used for experiments, filled with sand and gravel. Rover is placed inside for scale.

V. EXPERIMENTAL VALIDATION

For initial experiments and calibration the rover was placed on crates that supported its chassis and allowed the wheels to turn free without loading. After initial calibrations were completed, the rover was placed on a level surface on its wheels. The PID controllers for the wheel actuators were then calibrated under a real world loading environment using standard gravity.

Initial terrain testing and slip modelling experiments were performed in a wooden terrain box to allow interchangeable terrain, and provide a controlled environment. The test bed was just wider than the vehicle and measured 4.8 metres in length. Primary testing in this environment was done using sand and gravel, that were 100mm deep along the test area. This provided a convenient and controlled environment to test the various functionality of the rover under a controlled environment. This setup is shown in Fig. 5 including the terrain box and the rover within.

A. CENTRE OF ROTATION OFFSET EFFECT ON WHEEL ROTATION

The maximum revolutions per minute (rpm) achieved by a wheel is directly proportional to the rpm that the drive train can exert on the axle. A traditional rigid wheel simply rotates at the same velocity as the axle. The Posable Hubs are mechanically coupled to the axle as traditional wheels, however when manipulating their ride height, the actuation speed of the centre hub affects the maximum achievable rotation.

As the wheel does not rotate about its geometric centre, its actuators require time to keep the centre at the desired position. The time required is proportional to the actuation distance, as the further away from the geometric centre the hub is actuated, the greater the distance the actuators have to move. As a result the rover's maximum velocity, while actuating the wheels, is the defined as VA_{max}.

The time t_r for the actuators to move the centre hub in a full circle at different ride heights was experimentally measured and recorded in table 2. rpm can then be determined

$$rpm = \frac{60}{t_r}, \tag{8}$$

TABLE 2. **Maximum wheel velocity achievable at different ride height offsets.**

Ride Height Offset (mm)	Full Circle Time (s)	Full Circle Distance (mm)	Theoretical Max Velocity (rpm)	Theoretical Max Velocity (ms^{-1})
± 0	0	0	∞	∞
± 10	0.85	62.83	71	2.22
± 20	1.23	125.66	48	1.51
± 30	1.58	188.49	36	1.1
± 40	1.95	251.32	29	0.92
± 50	2.42	314.16	24	0.77

FIGURE 5. **Rover in a terrain box filled with sand and gravel used for initial experiments with debogging.**

and each value substituted to find VA_{max} using

$$VA_{max} = \frac{rpm * 2r * \pi}{60} \quad \forall rpm \tag{9}$$

where rpm is the wheel rpm and r is wheel radius. Table 2 shows the speeds obtained.

Table 2 shows that smaller ride height offsets are able to be achieved faster, as expected, and be maintained at higher wheel revolutions. Further to this table it is important to note that the motor can exert a maximum of 21 rpm on the axle, as a result the speed limiting component of this drive is the motor. On the extremities of the centre hub workspace, $\pm 50mm$, the actuators can maintain the position up to 24 rpm, the motor can only exert 21 rpm, therefore the actuators are of sufficient velocity to not inherit maximum velocity.

B. POSABLE HUB FOR DEBOGGING

Once the Posable Hubs were shown to not impact the maximum speed of rotation, its uses were tested for help with debogging, when the rover became stuck. The rover was placed in a sand environment and held until the front wheels dug a hole and got stuck. The timing belt on the rear wheels was then disconnected to de-couple the wheels from their motors and allow the rear wheels to become free turning. This was done to use the wheel axle encoders to show the true distance travelled, and compare wheel slip of the front (powered) wheels.

Using the rover in a 2-wheel-drive configuration also allowed for the rover to become stuck more easily, as the large radius tires and 4-wheel-drive gives it exceptional grip with the ground and is difficult to bog. Setup is shown in Fig. 5.

It was found that adjusting the effective vehicle wheelbase length helped the rover in becoming unstuck, from a bog that could not be freed by simply rotating the wheels. This required both the front wheels to extend forward, and the read wheel to extend backwards simultaneously. As the maximum workspace reach of the hub inside the wheel is 100mm, the overall wheelbase of the rover can be adjusted by 200mm. This allows for the overall wheelbase adjustment of 25% of the chassis designed fixed size.

Once the rover became stuck, the rear and front wheels were adjusted to contract or extend the wheelbase. This resulted in the front wheels being pushed and pulled out of the hole to regain traction. Fig. 6 shows the results.

As seen in Fig. 6, the front two wheels experienced a significant amount of slip as the rear, undriven, wheels remained stationary. At around a travelled distance of 0.25m the wheelbase was expanded by 100mm, which allowed the front wheels to regain traction and pull the vehicle forward. Once the rover became unstuck, the wheels were actuated again to their normal geometric state, to remove the need for constant readjustment, and limit the current usage. At around 0.75m, the rover became stuck again, the same debogging manoeuvre was performed to regain traction. Note the relationship of the wheel actuation with the magnitude of the current usage is somewhat limited.

Not actuating the wheels uses less current, however does not allow the rover to dig itself out of the hole. Injecting extra energy into the system to actuate the wheels, allows the bog to be overcome and vehicle to continue on its trajectory. In this experiment, the wheel actuation manoeuvre used 13% more power than when the wheels are completely passive, only for the required time. A significant benefit of this is that it only requires extra energy when being performed, once the vehicle is free of the bog, the wheels return to a normal state and use less power, maintaining the low Cost of Transport of wheels while offering the benefit of extra degrees of freedom, when compared to traditional wheels.

This experiment demonstrated that when a traditional wheel is stuck and unable to recover, using a Posable Hub to manipulate the rover wheelbase directly contributes to the rover recovering and becoming unstuck.

C. MOTORLESS MOTION

Motorless motion is a concept originally proposed in our previous paper [29]. This concept requires the centre hubs of the wheels to be offset in the horizontal axis, while the rim of the wheel remains stationary. Doing this creates a moment about the geometric centre of the wheel, as gravity is no longer acting through the origin of the axle. This in turn creates an unstable system and forces it to roll in an

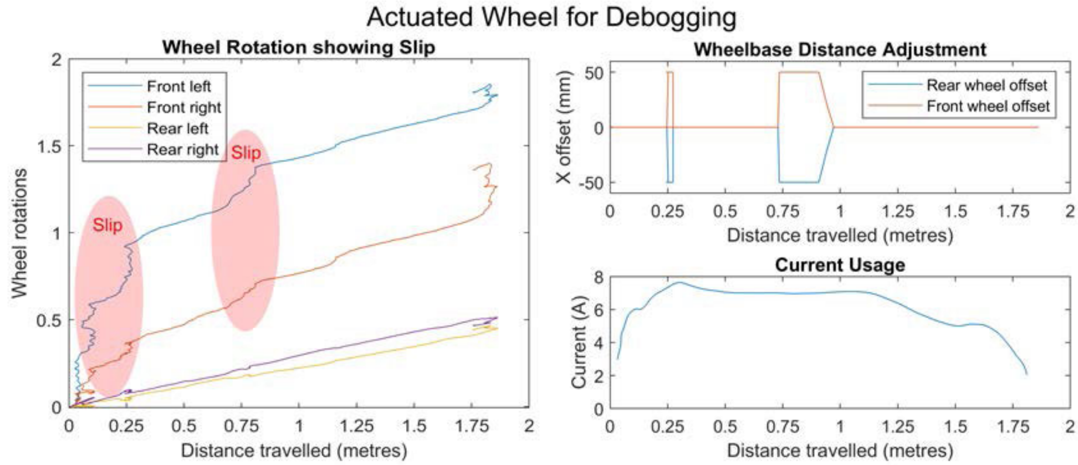

FIGURE 6. Fig. shows the data recorded during a debogging experiment. Front wheels extender forward while rear extended backwards, to increase the rover wheelbase. Two powered front and two free-turning rear wheels were used to record slip.

under-damped manner, in the horizontal direction of the centre hub offset. This method of generating locomotion requires a free-turning axle, or a clutch to decouple the existing drive motor (performed by manually removing the timing belt).

Paper [29] uses pneumatic cylinders to achieve this, with a focus on slopped terrain. Using a wooden beam connecting two wheels to conduct the preliminary experiments. This papers uses electric actuators to actuate the centre hub, on a four wheeled rover. The overall control system of this version is significantly more accurate and requires less power to run. Testing on a rover with four wheels also extrapolates real world applications and allows direct comparison to traditional wheels with a rotational motor drive.

The experiments performed for motorless motion consisted of using DC motors to drive each wheel and recording the IMU, current and velocity data of the rover driving with no wheel actuation. This required the wheels to act completely passive, with the centre hub locked in the geometric centre of the wheel. This experiment was performed to gather data of the system acting as a traditional rover. A secondary experiment consisted of decoupling the DC motor from the drive axle to allow free-tuning, via removing the timing belt from the drive train. This resulted in all four, previous driven wheels, becoming undriven and completely free turning.

The onboard computer then measured the quadrature encoders for the rotational position of each wheel, and adjusted the horizontal wheel offset accordingly. This resulted in exhibiting a Sustained Driving Gait [29], which required the centre hub position to be constantly readjusted to maintain a smooth chassis motion. These experiments were performed on a structured, continuous terrain of polished concrete, and on an asphalt road. The rover produced motion in the forward and backward direction, no steering manoeuvres were performed. The data is shown in Fig. 7.

Referring to Fig. 7, the left two graphs show data for our actuated wheel, while the graphs on the right show data for a traditional, unactuated wheel. Looking at the bottom two graphs, the DC motor driven wheels achieved a steady state velocity of $0.27ms^{-1}$ while consuming $2.3A$. Using Equation 7, the Cost of Transport is found to be 0.202. Likewise for the actuated wheel, using no DC motor, the CoT is 0.584 with a velocity of $0.4ms^{-1}$ and current usage of $4A$.

These differences in the CoT are to be expected as the unactuated wheel only requires a single DC motor to turn the drive train, maintaining its high efficiency. Energy losses in this instance are most evident through bearing/gear friction, motor heat, and noise. There is no evident loss of energy in the transfer of rotation from the axle to the wheel, as the wheel actuators are locked in place via their worm drives.

Using the motorless motion technique, with a free turning axle, the system complexity is increased. The axle is also mounted to pillow block bearings for support, and experiences loss of energy via friction. However, now there are three motors powering each actuator, and two mounting points per actuator. This results in extra friction being created in the geometry of the wheel as its centre hub moves. Each linear actuator also experiences friction and stiction along its entire length of actuation. A higher count of components interact with each other and create heat, therefore more energy is lost compared to a traditional wheel.

A further point made clear by the data in Fig. 7 is that the experiment was able to achieve a faster velocity when using energy from gravity than the specific drive motors used. This is directly because of the limitation of the rotational speed of the DC motor used for a traditional wheel. However, comparing the metres per second per ampere figure, the motorless motion technique achieved $0.1ms^{-1}A^{-1}$, while the traditional wheel achieved $0.117ms^{-1}A^{-1}$. This shows that velocity and current usage are proportional and overall not dissimilar between the two locomotion techniques.

Our proposal for the use of motorless motion driving technique is as a redundancy method. A DC drive motor proves more efficient however should the primary drive method fail, the motorless motion can be used with the disconnection of the drive motor. This method can also be used to assist in

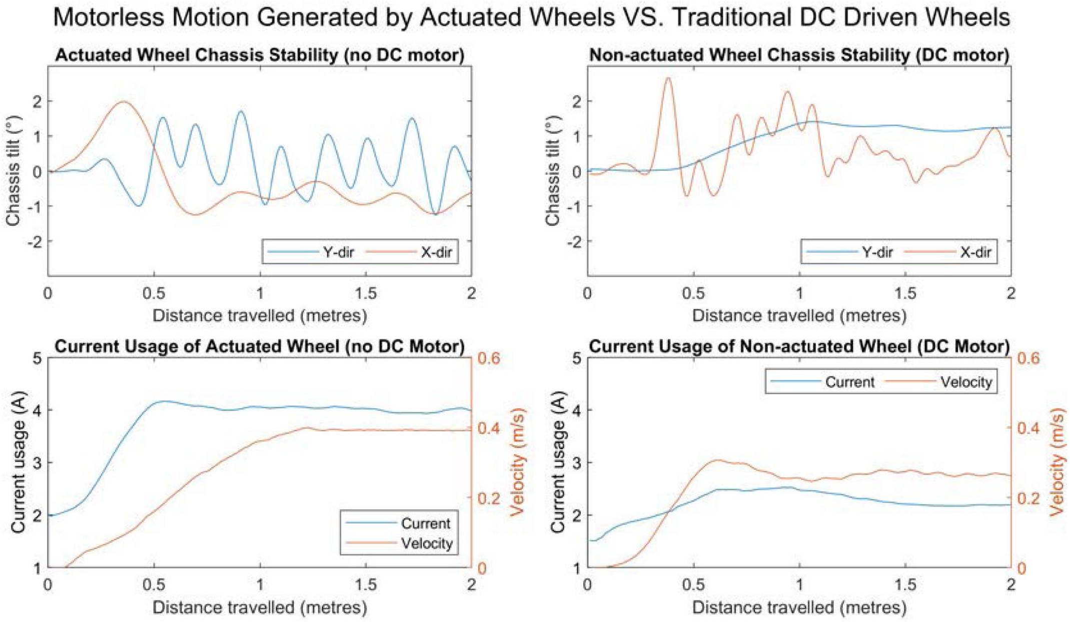

FIGURE 7. Shows the chassis stability, rover velocity and system current draw of a traditional wheel and DC motor model (right) as wells as a rover using our actuated wheels (left).

slope traversal by inducing further energy into the rover and shifting its centre of gravity uphill.

VI. FIELD DEPLOYMENT

After the initial experiments were successfully concluded, the platform was tested in the field. Tests performed were focused at exploring the use of adjusting the ride height of the individual wheels to maintain a level chassis on sloped terrains. The benefits of this functionality are in increased platform lateral stability, by controlling the chassis COG, the rover is less prone to rollovers on slopped terrain [30]. A sloped paved road was utilised as a test environment, as well as unstructured terrain on an unmaintained sloped track.

Further, if driving along the gradient of an incline, each wheel can be adjusted to maintain optimal COG and increasing rover stability by lowering the COG, or by shifting it uphill. The benefit of this functionality is the increased platform lateral stability, by controlling the chassis COG, the rover is less prone to rollovers on slopped terrain [30].

The experiments involved first driving the rover up and down the sloped terrains, with the wheels non actuated. This allowed for data to be recorded and later used for comparison to a traditional wheel. This was then repeated while the wheels were actively actuated, to hold the chassis level with gravity. Fig. 8 shows the chassis on a sloped grass area, with the wheels not actuated on the right side and wheels actively actuated on the left side. Similarly, Fig. 9 shows the same concept performed on a sloped, off-road track.

Figs. 8 & 9 show the chassis maintained at a completely level pose, as the workspace limits have not been reached. Fig. 10 however shows the slope too great for the rover to fully level the chassis, as the limits of wheel hub workspace has been reached. Limits are calculated in Section IV-B.

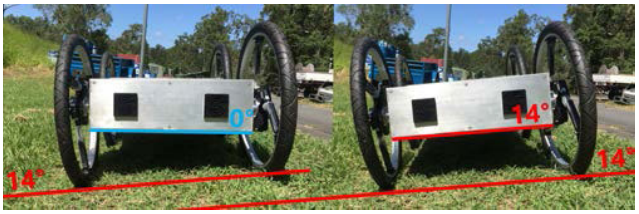

FIGURE 8. Fig. shown the rover on a sideways slope with unactuated wheels (right) and actuated wheels (left) holding the chassis level with gravity. The sideways slope has a gradient of 14 degrees.

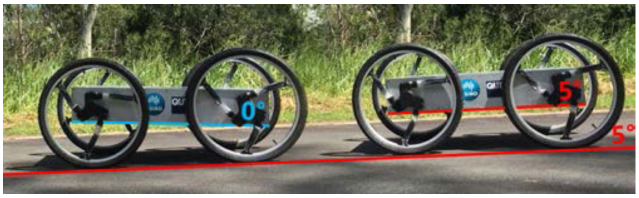

FIGURE 9. Fig. shows unactuated wheels (right), which demonstrated the natural chassis tilt in parallel with the slope of the road. Fig. also shows the wheels actuating to hold the chassis level with gravity (left). Road has a slope of 5 degrees.

FIGURE 10. Experiments preformed on unstructured terrain in the field. Fig. shows unactuated wheels (right) and actuated wheels (left) holding the chassis level to the extremities of the wheel hub workspace. Terrain slope is 12 degrees.

The data from these experiments is presented in Fig. 11. The left side of the Fig. shows the data from a sideways slope

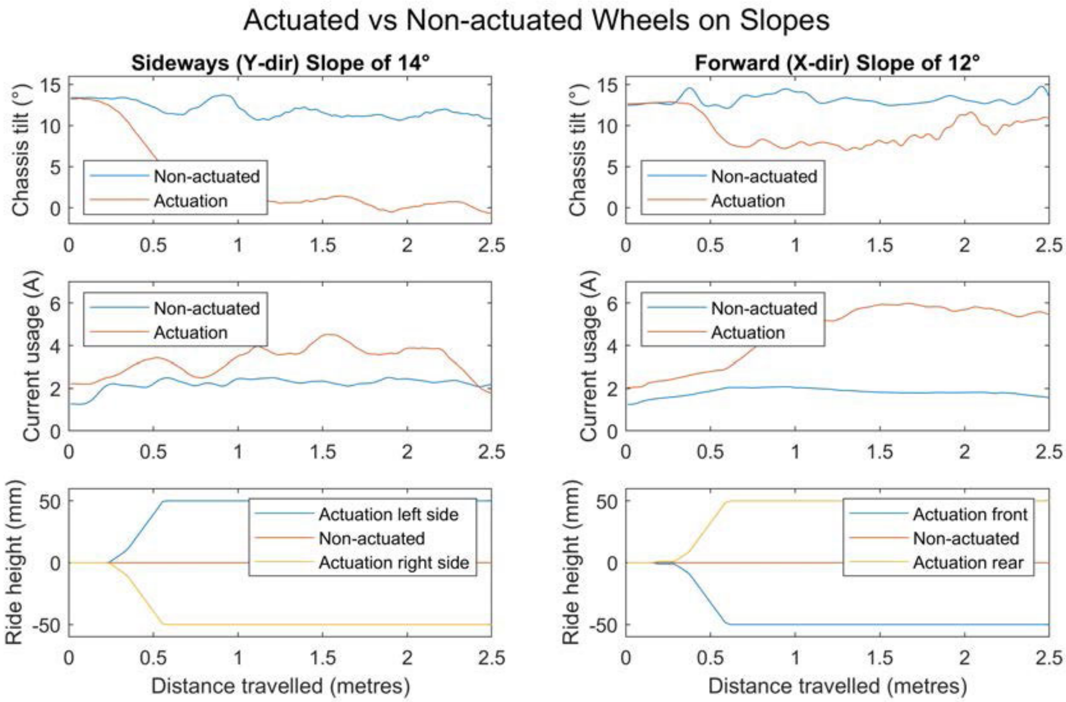

FIGURE 11. Data obtained during field tests of the Posable Hubs, actuating to mitigate the effect of slopes on the chassis pose. (left) shows a sideways slope of 14 degrees and (right) shows a forward slope of 12 degrees.

(as shown in Fig. 8) and the right side shows data from a forward slope (as shown in Fig. 10).

From the data plots it is clear that the Posable Hubs are able to significantly manipulate the chassis pose, only limited by the centre hub workspace and the overall chassis geometry. Data from the sideways slope shows the chassis being able to completely overcome the slope, and maintain the body at a level pose while using roughly 75% more current. This has an increase on the Cost of Transport of the rover, however, allows for a greater range of applications.

Likewise a forward slope of 12 degrees was tested on unstructured terrain. In this experiment the chassis was able to be adjusted by 5 degrees, due to the geometry of the system and highly uneven terrain. The system used about 250% more energy than the equivalent experiment with non actuated wheels. This great increase in current is partially due to the uneven terrain, requiring more adjustment, and the changed weight distribution of the chassis, resulting in some wheels experiencing higher loads.

Overall the experiment validated the functionally of the Posable Hubs in an uncontrolled field environment. The effects of slopes on chassis pose are able to be mitigated by the Posable Hubs, with the sacrifice of lower Cost of Transport. However, as the actuation can be controlled, the amount of extra power usage can be controlled to ensure it remains within the acceptable threshold.

VII. PERFORMANCE AND LESSONS LEARNED

Performing the experiments in the controlled test environments of indoor with air conditioning, indoor without air conditioning and and in the field proved useful as different functions of the Posable Hubs were able to be tested. A variety of terrains and terrain environments yielded some useful insights into the performance of the rover.

A. THERMAL

Initial testing of individual wheels was performed indoors at room temperature, under regulated air humidity and temperature. The actuators demonstrated desired performance and radiated heat into the surrounding air to maintain a cool operating temperature, with and without loading.

Secondary experiments were performed indoors, in an uncontrolled temperature environment with an average temperature of 30-35° Celsius. This increase in temperature contributed to the degraded performance of the actuators after some time, as they noticeably retained more heat and the motor coils became less efficient. The rover was allowed to cool before further experiments were performed.

Finally, testing the rover in a completely uncontrolled environment proved most difficult. In the field, the average air temperature was 30-35° Celsius, however as the rover was not undercover, the sun heated up the actuators to a significantly higher temperature. The actuator motor enclosing, and subsequent hub mounting points are constructed from black ABS plastic, this resulted in higher absorption of the sunlight and resulted in overheating of the actuators after minimal use.

Other components inside the chassis did not experience the same issue as the body is made from semi-reflective aluminium, and has four high flow fans to circulate air throughout for cooling. The addition of active cooling for the actuators would improve their performance. Chassis ventilation fans are shown in Fig. 2.

B. MECHANICAL STRESS

The Posable Hub wheels were built using off-the-shelf components with custom 3D printed mounts, and custom control setup. Due to each actuator mount requiring a degree of freedom, and overall wheel having six mounting point for actuators, measures were taken to reinforce these mounts and ensure the wheels in-plane stability is not compromised. For applications such as motorless motion and general chassis pose selection this setup was sufficient in controlling mechanical stresses felt by the rover chassis.

However, for debogging and slope traversal some of the mechanical points did not constrain the actuators enough, resulting in torsional stresses on the wheel, perpendicular to its rotation. This was most noticeable during slope traversal on unstructured terrain, as the wheels would slip and twist.

The current design is satisfactory for proof of concept, however further reinforcement or mounting point redesign is required for unstructured terrain with any increased payload on the rover.

C. CONTROL SYSTEM

Cost of transport was found to be directly linked to the amount of time the actuators were manipulating the position of the Posable Hub. Initial PID controllers were tuned and an overall control system was implemented for the control of the Posable Hubs position. However, as this is a prototype and we present the initial experiments, validating the functionality was a higher priority than tuning the control system.

Further work can be done to optimise the actuator, and overall controllers for the wheels. This can also include new functionality that has not yet been implemented into the system, such as lifting one wheel at a time and partially rotating the wheel before placing it down again, to achieve forward 'walking' with the Posable Hubs.

VIII. CONCLUSION

Space exploration and work such as search and rescue or resource mining is dangerous and often unsuited to manned platforms due to the associated dangers and costs. In the example of extra terrestrial exploration, unmanned rovers dominate the sector due to their lower cost and size as they do not have to house life support for astronauts. Further, due to remote or autonomus operation, no human life is endangered.

Rovers use various locomotion systems with wheels dominating the sector due to their simplicity and low Cost of Transport. However, wheeled system present significant drawback such as their limited ability to debog after becoming stuck in a sandy environment. Suspensions systems and mechanical design can limit this drawback however no solution exist that fully fill the gap with these requirements.

To address this, we propose the Posable Hub system using linear actuators to actively change the centre of rotation of the rim. We focus on constructing a rover utilising four Posable Hubs, theoretical calculations to show system advantages and limitations, and perform a number of field trials to prove the usefulness of the various benefits these wheels provide.

We validate the superiority of a Posable Hub in assisting in debogging operations. As a classical wheel only possesses one degree of freedom (DOF), rotation, it only has one way of getting out of bog, by rotating forward or backwards. Our wheel has three DOF and allows the centre hub to move around in the rim plane. This, as a result, allows for the wheel to be used in a clawing motion, while rotating, to free the rover from the bog by manipulaton its ground contact patch.

A number of further experiments and field trials are performed to evaluate the performance of other benefits of our system. We show the platform driving on various slopes of up to 14 degrees while keeping the chassis horizontally levelled, due to the ability of the wheels to adjust their ride height.

We further demonstrate the ability of the wheels to generate forward and backward linear motion by converting the gravitational potential energy to rotational motion of the wheels. Using the hubs to offset the centre of rotation, instability is introduced into the system and gravity generated a moment, which in turn generates linear motion of the rover, when the rotational drive motors have been decoupled from the axles. This in turn acts as a redundant locomotion technique.

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