

USING A ROVER'S ACTIVE SUSPENSION SYSTEM AS A 2-AXIS SOLAR TRACKER MECHANISM

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ABSTRACT

After successful completion of two 4-week field deployments in Utah (2016) and Morocco (2018), the SherpaTT rover is being prepared for further autonomous long-distance traverses in terrain akin to the Martian environment. However, it features a fueled power generator which cannot be employed in extra-terrestrial scenarios. As the rover is meant to approach a higher technology readiness level, a photovoltaic power subsystem is proposed to guide future design iterations. This paper presents the solar array sizing, design, and integration processes considered for two Martian mission sites: Iani Chaos at 2°S and Ismenius Cavus at 34°N. An alternative use case for the active suspension system is presented so that the proposed solar arrays may be inclined and oriented into power generating configurations that are more favorable than those achieved with passive suspension rovers. In the proposed scenarios, active solar cell orientation results in traverse gains of up to 34% and 25% for clear days at Iani Chaos and Ismenius Cavus, respectively.

1 INTRODUCTION

The exploration rover SherpaTT has a total mass of approximately 206 kg and the legs as well as the Robotic Arm (RA) weigh about 25 kg each. In standard pose the rover has a footprint of 240 cm x 240 cm. The wheeled-leg active suspension system allows the rover to assume different poses with varying inertial moments. The rover is one of many systems comprising a Multi-Robot System (MRS) developed at the German Research Center for Artificial Intelligence (DFKI)'s Robotics Innovation Center (RIC). The rover has undergone several field trial campaigns, particularly with a Mars analogue terrain field deployment in Utah, USA, where a logistics chain for sample return was evaluated using a MRS¹. The rover's versatility has been demonstrated through a multitude of tasks such as assembling surface deployable payloads and using its RA for soil sampling with modular Payload Item (PLI) sampling devices [1].

The actively articulated suspension system consists of four wheeled-legs with a total of 20 motors. Motor distribution across a single leg is shown in Figure 1. Each leg is equipped with three suspension motors and two drive motors.

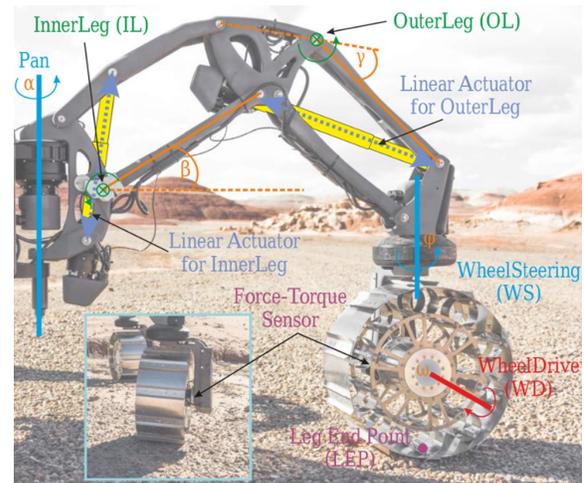


Figure 1: Description of DoF present in SherpaTT's actively articulated suspension system.

The suspension motors are responsible for Pan, InnerLeg (IL), and OuterLeg (OL) revolute joint rotations whereas the drive motors are responsible for WheelSteering (WS) and WheelDrive (WD). A first design iteration of the rover with Solar Array (SA) for an Ismenius Cavus deployment is shown in Figure 2.



Figure 2: SA for Ismenius Cavus deployment.

¹ <https://youtu.be/pvKIzldni68>

In a second field deployment, the rover was tested for a long autonomous traverse in the desert of Morocco [2]. The rover displayed the ability to cope with natural terrain and to fulfill the task of autonomously traversing 1.4km in approximately 8 hours². Further development is required on its electrical power sub-system if it is to operate in long term missions. This paper explores SA configurations for a Mars environment as a guide for future design iterations aimed at navigating the topography of this planetary surface. The constraints imposed from the active suspension system with flexible footprints and varying heights of structural parts of the legs are considered in the design phase.

Initial SA sizing requirements are derived from Mars mission sites, Iani Chaos and Ismenius Cavus, that impose energy storage and consumption constraints based on available daily insolutions. The design is driven by the use the rover's active suspension system as a 2-axis solar tracking mechanism, enabling daily reconfiguration of the SA surface inclination and orientation angles. An alternative use of the wheeled leg system is thus presented for a use case that goes beyond the scenario of negotiating complex terrains such as steep slopes. Specifically, the findings demonstrate traverse and mass reductions gains that are obtained with a suspension system driven inclination and orientation capable SA surface when compared to a horizontal configuration.

Past research on active suspension systems are restricted to analyzing benefits with respect to traversing challenging topographies. Studying how this system can be used for other mission planning elements broadens the field of research.

2 POWER BUDGET

Large inclination angles are typically preferred with respect to increased insolation for a sun-facing surface. However, constraints on the rover's active suspension system impose a limit on the achievable body pitch angle. Body pitch commands of up to 10° are experimentally evaluated during steep slope climbing in [3]. Modeling higher pitch angles resulted in poor wheel-ground contact angle due to the WS axis having the same tilt as the rover's body. The attainable tilt is thus restricted resulting in a maximum SA surface inclination angle of $\beta_{max} = 10^\circ$ in this study.

Table 1 and Table 2 present daily insolutions H_h , on horizontal SA surface, compared to those obtained

with H_β , on an inclined sun-facing SA surface, for best and worst case areocentric longitudes (L_s).

Table 1: Worst and best case daily insolutions at Iani Chaos.

τ	Worst Case				Best Case			
	L_s	H_h	H_β	gain	L_s	H_h	H_β	gain
0.1	80	3232	3721	15.13	221	5076	5695	12.19
0.4	81	2909	3166	8.85	218	4613	4933	6.93
0.5	81	2812	3025	7.58	218	4473	4736	5.89
1.0	82	2391	2479	3.67	214	3855	3959	2.69
1.5	82	2087	2125	1.81	213	3403	3444	1.19

Optical depths τ for clear to dusty days are evaluated with the daily insolutions expressed in Whm^{-2} and the gains in percentage. The solar insolation values are taken from [4] and obtained with Mars solar radiation formulas in [5], [6], [7], [8], and [9].

Table 2: Worst and best case daily insolutions at Ismenius Cavus.

τ	Worst Case				Best Case			
	L_s	H_h	H_β	gain	L_s	H_h	H_β	gain
0.1	274	2102	2762	31.42	127	4421	4925	11.40
0.4	273	1752	2030	15.85	125	4028	4289	6.49
0.5	273	1655	1869	12.93	124	3908	4122	5.48
1.0	273	1284	1345	4.75	121	3378	3461	2.44
1.5	273	1045	1061	1.57	120	2945	2973	0.96

Daily insolation gains obtained with an inclined surface are more pronounced for sites further away from the equator. For a typical optical depth of τ factor 0.4, the average daily insolation gain with an inclined surface is approximately 7% at Iani Chaos and 9% at Ismenius Cavus.

The mostly diffuse composition of solar irradiance at higher optical depths make inclined surfaces irrelevant in global dust storms. For $\tau \geq 2$, gains in daily insolation become negligible at both sites.

As a prerequisite to SA sizing, power budgets are defined for hibernation and flat terrain traverse reference Sols. These are presented in Table 3 and Table 4. Hibernation power draws are identical during day

² <https://youtu.be/-zqve9baOzM>

and nighttime, so the hibernation reference Sol does not have a best or worse case Sol with respect to available sunlight.

Table 3: Hibernation Sol power budget.

Mode	P [W]	Iani Chaos		Isenius Cavus	
		t [min]	E [Wh]	t [min]	E [Wh]
Day	18	720	216	720	216
Night	18	720	216	720	216
<i>Total</i>	<i>36</i>	<i>1440</i>	<i>432</i>	<i>1440</i>	<i>432</i>
<i>+20% Margin</i>	<i>43</i>	<i>-</i>	<i>518</i>	<i>-</i>	<i>518</i>

Durations of daylight dependent modes in the traverse reference Sol are based on the total length of daylight time for worst case daily insulations Sols presented in Table 1 and Table 2 with τ factor 1 and $\beta = 10^\circ$ for the SA surface inclination angle. Propulsion power draws for the rover's flat terrain traverse mode is determined from data collected during the SherpaTT Utah field trial [1, 3].

The *Optimal Pose* mode in Table 4 consists of using the rover's active suspension system to reconfigure the SA surface orientation and inclination so that daily insolation is maximized for the following Sol. The suspension system thus undertakes the role of a 2-axis solar tracking mechanism. This study does not evaluate continuous solar tracking, the SA are oriented once at the end of each Sol for optimum power generation.

Table 4: Worst case flat traverse Sol power budget, $\tau = 1$ and $\beta = 10^\circ$.

Mode	P [W]	Iani Chaos $L_s = 81^\circ$		Isenius Cavus $L_s = 273^\circ$	
		t [min]	E [Wh]	t [min]	E [Wh]
Idle - Day	29	603	291	464	224
Communication	52	35	30	35	30
Traverse	113	4.8	9	4.8	9
Science Stop	60	60	60	60	60
Optimal Pose	75	12	13	10	13
Idle - Night	20	242	242	866	289
<i>Total</i>	<i>349</i>	<i>1440</i>	<i>646</i>	<i>1440</i>	<i>625</i>
<i>+20% Margin</i>	<i>419</i>	<i>-</i>	<i>775</i>	<i>-</i>	<i>750</i>

3 SOLAR ARRAY SIZING

The solar cell coverage area A is expressed as:

$$A = E / \eta \cdot H_\beta \cdot PR$$

where E is the rover's energy requirement, η is the solar cell efficiency, H is the daily insolation, and PR is the solar cell performance ratio.

Two approaches are taken for SA sizing: First a worst-case scenario with high optical opacities and second an inverse approach with target solar cell coverage areas.

The initial SA sizing is determined with H_β from Table 1 and Table 2 as well as E from Table 4 for the worst case daily insolation at τ factor 1. End of Life (EOL) values for PR and η are determined in [4]:

- (1) $H_\beta = 2479 \text{ Whm}^{-2}$, $E = 775 \text{ Wh}$ at Iani Chaos
- (2) $H_\beta = 1345 \text{ Whm}^{-2}$, $E = 750 \text{ Wh}$ at Isenius Cavus
- (3) $PR_{EOL} = 0.62$
- (4) $\eta_{EOL} = 0.22$

The solar cell packing efficiency is assumed at 85%, the SA surface density at 3.7 kgm^{-2} , and the average slippage at 15% when traversing a flat terrain for any given distance. Traversing is constrained to daylight hours and it is assumed that average traversing only occurs every third Sol. At Iani Chaos, the required SA area is 2.7 m^2 and the mass 9.95 kg . SA surface inclination of 10% with a daily sun-facing reorientation results in a SA size decrease of 3.9% when compared against a horizontal surface configuration. The maximum flat traverse distance achievable over the course of a Martian year is increased by 13.22% from 42.43 km to 48.04 km with τ factor 1 during the global dust storm season and 0.4 otherwise. At Isenius Cavus, the required SA area is 4.8 m^2 , its mass 17.8 kg , and a 4.6% SA size decrease is achieved. The maximum flat traverse distance achievable over the course of a Martian year is increased by 2.13% from 63.05 km to 64.39 km .

The traverse distance gains attributed to SA inclination capabilities do not justify taking advantage of the rover's active suspension system for the purpose of increasing solar power generation. This is particularly true at Isenius Cavus. The savings in SA size and mass also leave much to be desired. Furthermore, the large SA are problematic in terms of rover integration. This is illustrated in Figure 3.

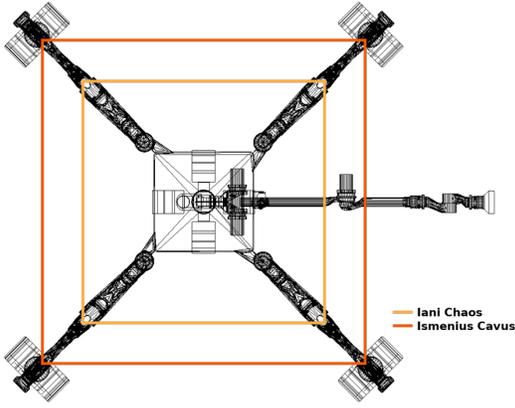


Figure 3: Initial SA sizing. The outlined square areas are equivalent to SA areas 2.7 m^2 for Iani Chaos and 4.8 m^2 for Ismenius Cavus.

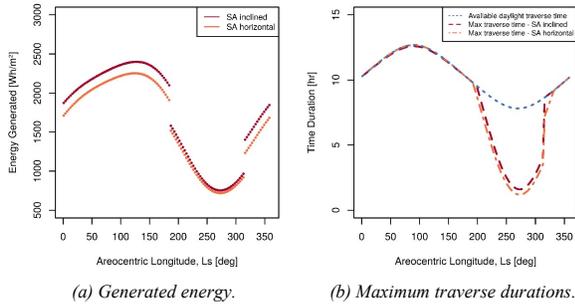


Figure 4: Generated energy and maximum flat terrain traverse duration at Ismenius Cavus. 4.1 m^2 solar cell coverage area. Surface inclination angle β is 10° , τ factor 1 for global dust storm season ($185^\circ < L_s < 315^\circ$) and 0.4 otherwise. The “available daylight traverse time” is the amount for daylight hours left in a Traverse Sol after subtracting the time taken by rover modes unrelated to traversing.

To explain the lack of significant gains, the generated SA energy and maximum traverse durations are plotted in Figure 4 for Ismenius Cavus. During clear days at τ factor 0.4, a ceiling is imposed on the daily maximum traverse durations due to insufficient daylight time for traversing. The maximum traverse time is already attained with a horizontal SA, making an inclined SA irrelevant in terms of traverse distance gains. As seen in Figure 4b, the inclined SA is only slightly advantageous during the global dust storm season with a τ factor of 1.

However, Figure 5b reveals no maximum traverse duration ceiling that could explain the poor gains observed at Iani Chaos. At both sites, lack of traverse distance gains is thus more closely tied to the τ factor selected when defining the worst-case reference Sol during SA sizing. At high optical opacities, increased light scattering by airborne Martian dust results in $H_\beta \approx H_h$ due to diffuse insolation being the largest component in the global insolation. Thus, when SA sizing for power generation during dusty Sols, the resulting inclined SA surface yield little to no benefits over horizontal surfaces with respect to traverse distance gains as well as with SA mass and area.

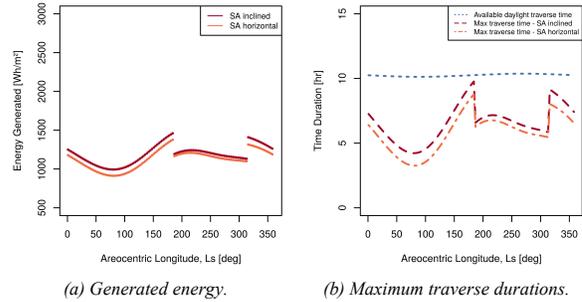


Figure 5: Generated energy and maximum flat terrain traverse duration at Iani Chaos. 2.3 m^2 solar cell coverage area. Same considerations as Figure 4.

The worst case power budget in Table 4 is set aside and the SA sizing process is approached inversely by identifying solar cell coverage area targets based on the traverse distance gains brought about by an inclined surface. Figure 6 compares the traverse distance gains obtained with an inclined SA surface for different solar cell coverage areas and optical depths.

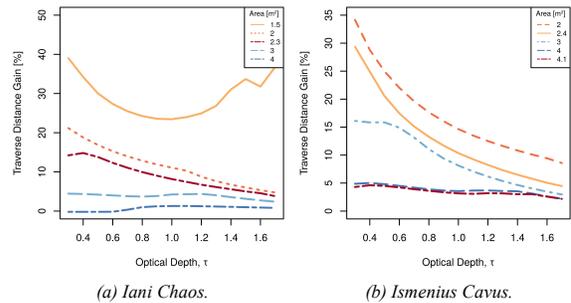


Figure 6: Average flat terrain traverse distance gains for different solar cell coverage areas. SA inclination angle $\beta_{\max} = 10^\circ$ with orientation angles γ_c set to their optimal values for the considered traverse Sols.

Targeting a solar cell coverage area of 1.5 m^2 at Iani Chaos results in an average 34% gain in traverse for a clear day at τ factor 0.4. The gain remains significant at 23% for a dusty day at τ factor 1. The increase in gain observed for τ factors greater than 1 are inconsequentially tied to negligible distances. At Ismenius Cavus, a solar cell coverage area of 2.4 m^2 results in 25% and 10% gains for τ factor 0.4 and 1, respectively. Applying the same packing efficiency and SA surface density as the initial sizing results in SA areas of 1.7 m^2 at Iani Chaos with a mass of 6.3 kg and 2.8 m^2 at Ismenius Cavus with a mass of 10.4 kg. The maximum daily traverse durations attainable at both sites with these target SA areas are shown in Figure 7. However, these gains come with significantly reduced maximum flat traverse distance coverage of 12 km at Iani Chaos and 35 km at Ismenius Cavus. Mission design with or without SA surface inclination thus not only depends on SA size and mass constraints but also on mission requirements with respect to target traverse coverages.

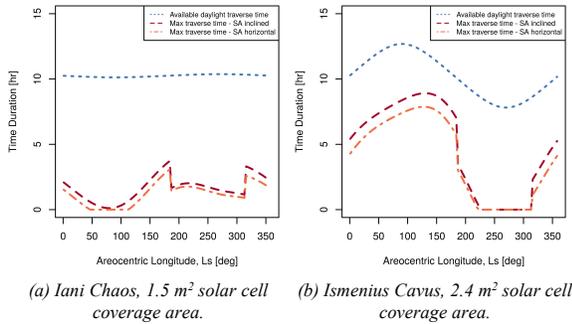


Figure 7: Maximum traverse durations at mission sites. Same considerations as Figure 4.

SA sizing with the hibernation reference Sol power budget defined in Table 3 as the worst case power budget fails to meet the target SA areas. However, the required power draws only differ by a few Watts. At Iani Chaos, this is achieved by reducing the hibernation mode power draws from 18 W to 17 W. At Ismenius Cavus, hibernation power draws need to be reduced from 18 W to 15 W. Taking into account a 20% system margin, the energy requirement for hibernation Sols become 490 Wh at Iani Chaos for a 1.7 m^2 SA area and 432 Wh at Ismenius Cavus for a 2.8 m^2 SA area. Figure 8 shows the rover's body redesign from a pyramid to a cubic shape to better accommodate the SA surface and avoid shadowing.

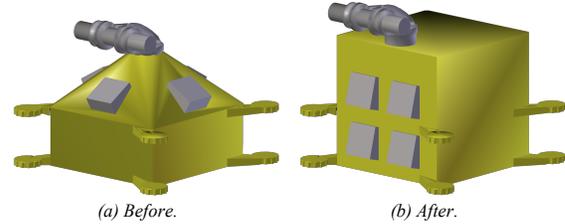


Figure 8: Rover body redesign.

4 SIMULATION

The proposed rover and SA configurations are modeled with Blender/Phobos and loaded into the MARS simulation environment for mission scenario simulation. Phobos is “an add-on for the open-source 3D modeling software Blender that enables the creation of robot models for use in robot frameworks like ROS and ROCK or in real-time simulations such as MARS” [10]. MARS is “a cross-platform simulation and visualization tool created for robotics research. It consists of a core framework containing all main simulation components, a GUI (based on Qt), 3D visualization (using OSG) and a physics engine (based on ODE)” [11].

4.1 Z-Axis Revolutions

Figure 9a and Figure 9b are two different representations of the same solar power output obtained from commanding the rover to execute a 10° forward body-pitch followed by several revolutions around its z-axis. These revolutions result in a sinusoidal power output variation. Local spikes and dips are noted around 100 s and 160 s due to small changes in the SA inclination and orientation angles caused by the rover driving over uneven terrain. In Figure 9b the angle values represent the direction faced by the inclined SA. Maximum power is generated when the SA is oriented towards the equator, in the general direction of the sun. Inversely, facing away from the sun, generates the least amount of power. These are the expected results thus validating the simulation environment for further development and mission scenario analysis.

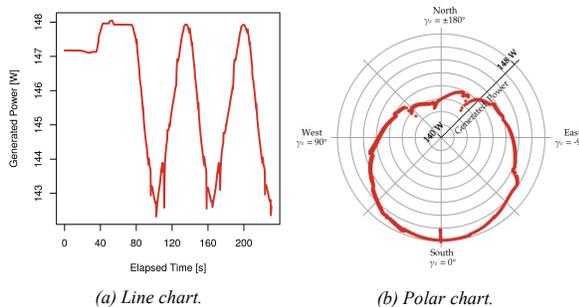


Figure 9: Power generated by the rover's SA during revolutions along its z-axis. Simulation condition is solar noon at Ismenius Cavus with $\beta \approx 10^\circ$. Polar chart angle values represent the direction faced by the inclined SA where 0° is South (towards the equator), -90° is East, 180° is North, and 90° is West.

4.2 Slope Compensation

The worst-case slope traverse is on an inclined surface facing away from the sun. The rover's active suspension system can be used to reduce the SA inclination angle by commanding a rover body pitch in the opposite direction. This slope compensation scenario is illustrated in Figure 10 where B denotes the slope surface inclination angle and β the SA surface inclination angle. By way of example, at Ismenius Cavus for a τ factor of 0.4 and L_s of 270° , descending a 30° slope bearing North results in a daily insolation of 319 Whm^{-2} . This is increased to 767 Whm^{-2} by decreasing β from 30° to 25° after tilting the rover southwards by 5° so that $\beta < B$. A 10° tilt would increase the daily insolation to 1046 Whm^{-2} with $\beta = 20^\circ$. The solar power generated from this scenario is simulated.

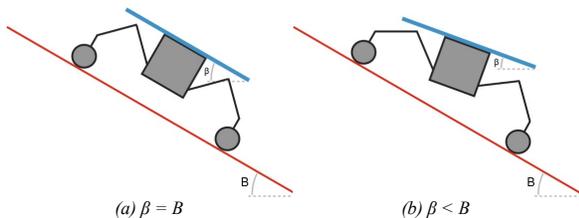


Figure 10: Slope compensation with active suspension system to reduce the SA surface inclination angle. Slope inclination angle $B = 30^\circ$. In (a), $\beta = B = 30^\circ$. In (b), the rover is tilted 10° in the opposite direction of the slope so that $\beta = 20^\circ$.

Figure 11 shows solar power outputs for different body-pitch configuration while the rover is on a 30° slope. The initial state of the SA surface inclination angle is equal to that of the slope angle. Two separate

5° forward pitch increments are executed at 25 s and 35 s which worsen solar power output by changing the SA surface inclination angle from $\sim 30^\circ$ to $\sim 40^\circ$. Four separate 5° backward pitch decrements are executed from 45 s to 65 s, progressively improving power generation as β is decreased from $\sim 40^\circ$ to $\sim 20^\circ$. As a final task, the rover is commanded to drive forward at 80 s and it encounters uneven terrain which introduces minor fluctuations to the solar power output.

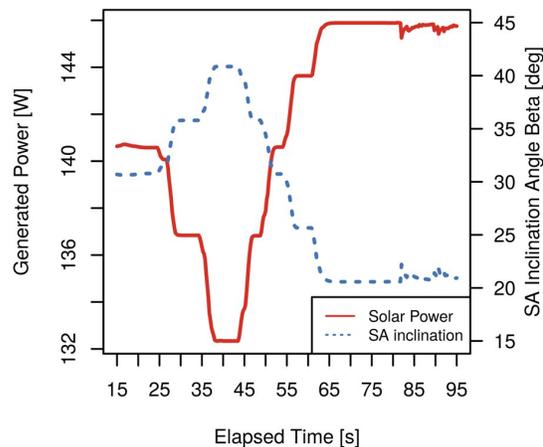


Figure 11: Simulation results of solar power generation on an inclined slope at Ismenius Cavus during solar noon.

5 CONCLUSION

The findings of this paper support using the SherpaTT rover active suspension system as a mechanism for solar panel inclination and orientation under certain SA sizing conditions. Combining a maximum attainable SA surface inclination angle of 10° with optimal daily orientation angles results in appreciable traverse gains when compared to what is obtained from a horizontal surface. However, this is not true for large SA areas. Furthermore, the smaller the required solar cell coverage area the greater the gains. Considering this, SA sizing for the worst case daily insulations introduces a hibernation mode solar power draw constraint of 17 W near the equator at 2°S and 15 W in the northern hemisphere at 34°N . With these power budgets, an average traverse gain of 34% is achieved at 2°S for a clear day with a τ factor of 0.4. At 34°N , the average gain is 25% under the same atmospheric opacity. These gains remain significant on dusty days at 23% and 10% at respective latitudes with a τ factor of 1.

This paper presents an active suspension system use case that goes beyond negotiating complex terrains such as steep slopes or exploring crater environments. The following are a few suggested research topics that expands this idea:

- (1) Conduct a power budget cost-benefit analysis with respect to the power draws from the suspension systems motors that are required to obtain the sun-facing inclined SA surfaces power gains.
- (2) Achieve higher pitch and rolls angles so that higher SA surface inclination angles may be attained.
- (3) Simulate ground adaption scenarios that preserve a desired SA surface position into a fixed plane.
- (4) Simulate shadowing events on the SA and analyze their effect on power outputs, particularly for shadows caused by the RA.
- (5) Implement a battery model to simulate battery charge and discharge for a more complete power subsystem simulation.
- (6) Develop power budgets for onboard instruments to simulate high power draw scenarios such as drilling for sample return missions.
- (7) Propose SherpaTT SA designs for terrestrial and lunar mission scenarios.
- (8) Explore other alternative use cases for the rover's active suspension system such as nighttime star tracking for astronomical observations with a mounted telescope.

At the time of writing this paper, work is already being done in (5) as part of the ADE (OG10) project for autonomous decision making in very long traverses [12].

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