Using a Rover's Active Suspension System as a 2-Axis Solar Tracker Mechanism

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***Abstract*— The SherpaTT rover is 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-terrestial 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. This results in traverse gains of up to $34\,\%$ and $25\,\%$ for clear days at Iani Chaos and Ismenius Cavus, respectively.**

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1. Introduction

The exploration rover SherpaTT has a total mass of approximately $160\,\mathrm{kg}$ and the legs as well as the Robotic Arm (RA) weigh about $25\,\mathrm{kg}$ each. 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. 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 [2].

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

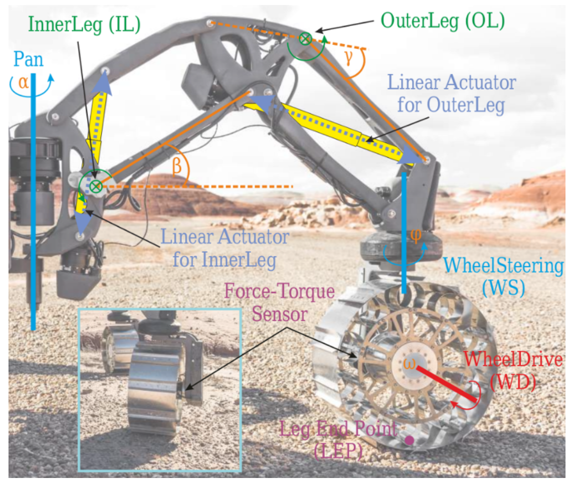


Figure 1: Description of DoF present in SherpaTT's suspension system and placement of force-torque sensor

The rover has been deployed in several field experiments where it was put under test within natural and unstructured Mars analogue terrain with respect to general morphology and geology. The rover displayed the ability to cope with natural terrain and to fulfill the task of being an exploration and sampling rover. Further development is required on its electrical power subsystem if it is to operate in long term missions. This paper explores Solar Array (SA) configurations for the a Mars environment in order to guide future design iterations to navigate 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 insolations. 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 imposes a limit on the achievable body pitch angle. Body pitch commands of up to 10° are experimentally evaluated during steep slope climbing in [1]. 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 $\beta = 10°$.

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

	Worst Case				Best Case			
τ	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

Table 1 and Table 2 presents the best and worst case daily insolations H_h, on horizontal SA surface, compared to those obtained with H_β, on an inclined sun-facing SA surface. Optical depths τ for clear to dusty days are evaluated with the daily insolations expressed in $\mathrm{Wh\,m^{-2}}$ and the gains in percentage. The solar insolation values are taken from [3].

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

	Worst Case				Best Case			
τ	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

Gains obtained in daily insolation with an inclined surface are more pronounced for sites further away from the equator. For a typical optical depth of $\tau = 0.4$, the average daily insolation gain on the inclined surface is approximately $7\,\%$ at Iani Chaos and $9\,\%$ at Ismenius Cavus. Due to the mostly diffuse composition of solar irradiance at higher optical depths, inclined surfaces become irrelevant during 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 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.

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

Durations of daylight dependent modes in the traverse reference Sol are based on the total length of daylight time for worst case daily insolations Sols presented in Table 1 and Table 2 with τ factor 1 and $\beta = 10°$ 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.

Table 4: Worst case flat traverse Sol power budget, τ = 1 and $\beta = 10°$.

		Iani Chaos $Ls = 81°$		Ismenius Cavus $Ls = 273°$	
Mode	P [W]	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
Total	349	1440	646	1440	625
+20% Margin	419	-	775	-	750

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 on the following Sol. In this manner, the suspension system undertakes the role of a 2-axis solar tracking mechanism.

3. SOLAR ARRAY SIZING

The solar cell coverage area A is expressed as:

$$A = \frac{E}{\eta \cdot H \cdot PR} \tag{1}$$

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. An 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 [3]:

(1) $H = 2479\,\mathrm{Wh\,m^{-2}}$ and $E = 775\,\mathrm{W\,h}$ at Iani Chaos.
(2) $H = 1345\,\mathrm{Wh\,m^{-2}}$ and $E = 750\,\mathrm{W\,h}$ at Ismenius Cavus.
(3) $PR_{EOL} = 0.62$.
(4) $\eta_{EOL} = 0.22$.

Furthermore, the solar cell packing efficiency is assumed at $85\,\%$, the SA surface density at $3.7\,\mathrm{kg\,m^{-2}}$, and the average slippage at $15\,\%$ when traversing a flat terrains for any given distance. Traversing is constrained to daylight hours and it is assumed that on average traversing only occurs every third Sol.

At Iani Chaos, the required SA area is $2.7\,\mathrm{m^2}$ and the mass $9.95\,\mathrm{kg}$. 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 $42.43\,\mathrm{km}$ to $48.04\,\mathrm{km}$ with τ factor 1 during global dust storm season and 0.4 otherwise. At Ismenius Cavus, the required SA area is $4.8\,\mathrm{m^2}$, 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 $63.05\,\mathrm{km}$ to $64.39\,\mathrm{km}$.

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 Ismenius 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 2.

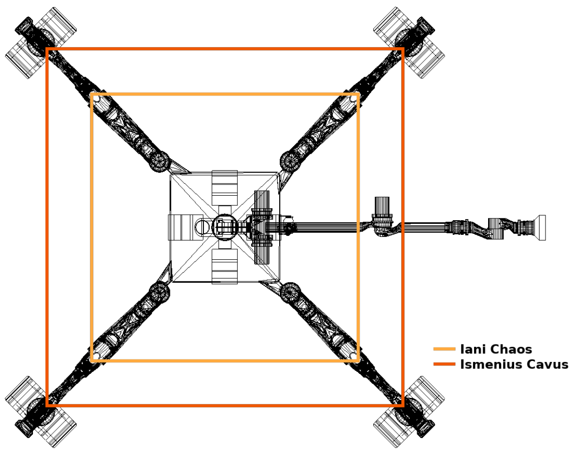
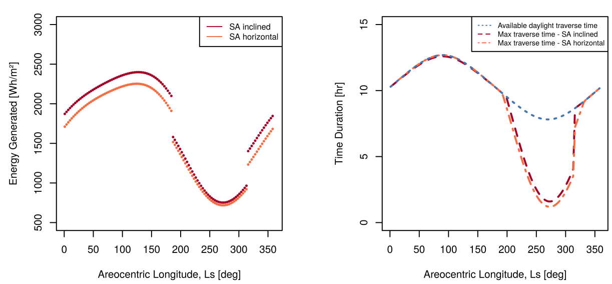


Figure 2: Initial SA sizing. The outlined square areas are equivalent to SA areas of $2.7\,\mathrm{m}^2$ for Iani Chaos and $4.8\,\mathrm{m}^2$ for Ismenius Cavus.

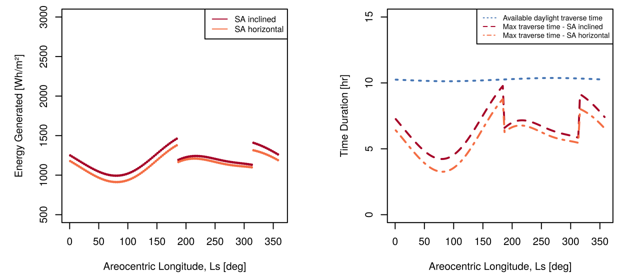
To explain the lack of significant gains, the generated SA energy and maximum traverse durations is plotted in Figure 3 for Ismenius Cavus. During clear days at τ factor 0.4, a ceiling is imposed on the daily maximum traverse durations due to the available daylight time for traversing. The maximum traverse time is already attained with a horizontal SA, making an inclined SA irrelevant in terms traverse distance gains. As seen in Figure 3b, the inclined SA is only slightly advantageous during the global dust storm season with a τ factor of 1.



(a) Generated Energy **(b) Maximum Traverse Durations**

Figure 3: Generated energy and maximum flat terrain traverse duration at Ismenius Cavus with solar cell coverage area of $4.1\,\mathrm{m}^2$. Surface inclination angle β is $10°$. τ factor 1 is used for global dust storm season ($185° \leq L_s \leq 315°$) and 0.4 otherwise. The *available daylight traverse time* corresponds to the amount of daylight hours left in a *Traverse Sol* after subtracting the time taken by rover modes unrelated to traversing.

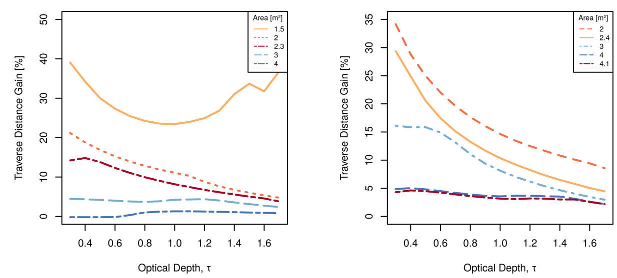
However, no such ceiling can be observed for Iani Chaos in Figure 4 which would explain the poor gains for that mission site scenario. In both cases, lack of traverse distance gains is more closely tied to the τ factor selected when defining the worst case reference Sol that drives SA sizing. At high 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 SA mass and area.



(a) Generated Energy **(b) Maximum Traverse Durations**

Figure 4: Generated energy and maximum flat terrain traverse duration at Iani Chaos with solar cell coverage area of $2.3\,\mathrm{m}^2$. The same considerations were taken as in Figure 3.

To resolve this, 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 5 compares the traverse distance gains obtained with an inclined SA surface for different solar cell coverage areas and optical depths.

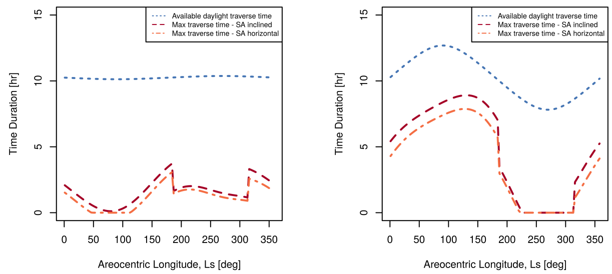


(a) Iani Chaos **(b) Ismenius Cavus**

Figure 5: Average flat terrain traverse distance gains at mission sites for different solar cell coverage areas. SA inclination angle $\beta_{max} = 10°$ with orientation angles γ_c set to their optimal values for the considered traverse Sols.

Targeting a solar cell coverage area of $1.5\,\mathrm{m}^2$ 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 observe for τ factors greater than 1 are inconsequentially tied to negligible distances. At Ismenius cavus, a solar cell coverage area of $2.4\,\mathrm{m}^2$ 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 $1.7\,\mathrm{m}^2$ at Iani Chaos with a mass of $6.3\,\mathrm{kg}$ and $2.8\,\mathrm{m}^2$ at Ismenius Cavus with a mass of $10.4\,\mathrm{kg}$. The maximum daily traverse durations attainable at both sites with these target SA areas are shown in Figure 6. However, these gains come with significantly reduced maximum flat traverse distance coverage of $12\,\mathrm{km}$ at Iani Chaos and $35\,\mathrm{km}$ at Ismenius Cavus. Mission design with or without SA surface inclination thus not only depend on SA size and mass constraints but also on mission requirements with respect to target traverse coverages.

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



(a) Iani Chaos, solar cell coverage = $1.5\,\mathrm{m}^2$

(b) Ismenius Cavus, solar cell coverage area = $2.4\,\mathrm{m}^2$

Figure 6: Maximum traverse durations at mission sites. The same considerations were taken as in Figure 3.

only differ by a few Watts. At Iani Chaos, this is achieved by reducing the hibernation mode power draws from $18\,\mathrm{W}$ to $17\,\mathrm{W}$. At Ismenius Cavus, hibernation power draws need to be reduced from $18\,\mathrm{W}$ to $15\,\mathrm{W}$. Taking into account a $20\,\%$ system margin, the energy requirement for hibernation Sols become $490\,\mathrm{W\,h}$ at Iani Chaos for a $1.7\,\mathrm{m}^2$ SA area and $432\,\mathrm{W\,h}$ at Ismenius Cavus for a $2.8\,\mathrm{m}^2$ SA area. A first iteration of the rover with a SA for an Ismenius Cavus deployment is shown in Figure 7.

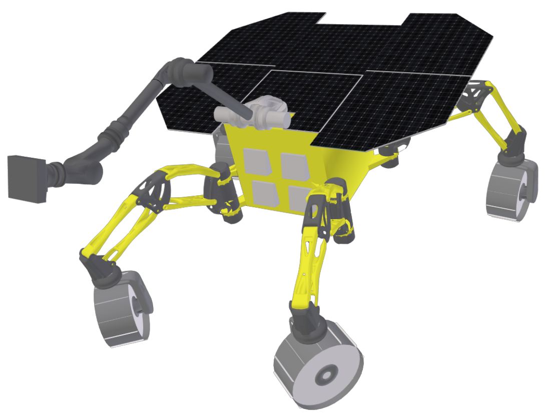


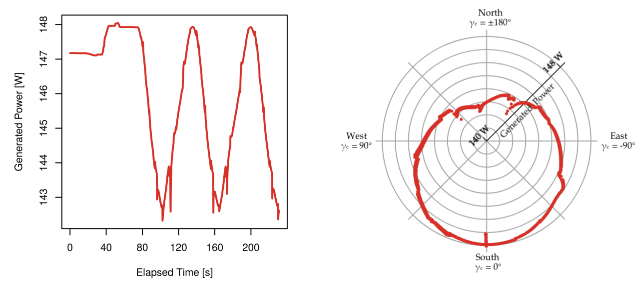
Figure 7: Rover with SA for Ismenius Cavus deployment.

4. Simulation

The proposed rover and SA configurations are modeled with Blender/Phobos and loaded into MARS 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" [4]. 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)" [5].

Z-Axis Revolutions

Figure 8a and Figure 8b 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 $100\,\mathrm{s}$ and $160\,\mathrm{s}$ due to small changes in the SA inclination and orientation angles caused by the rover driving over uneven terrain. In Figure 8b, the angle values represent the direction faced by the inclined SA. Maximum power is generated when the SA is oriented southwards, towards the equator, in the general direction of the sun. Inversely, facing northwards, away from the sun, generates the least amount of power.

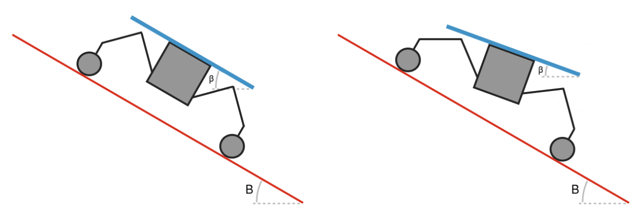


(a) Line chart **(b) Polar chart**

Figure 8: Power generated by the rover's SA for multiple revolutions along its z-axis. Simulation condition is solar noon at Ismenius Cavus with $\beta \approx 10°$**. In the 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.**

Slope Compensation

The worst case slope traverse is an on 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.



(a) $\beta = B$ **(b)** $\beta < B$

Figure 9: Slope compensation with active suspension system to reduce the SA surface inclination angle. Slope inclination angle $B = 30°$**. In (a),** $\beta = B = 30°$**. In (b), the rover is tilted** $10°$ **in the opposite direction of the slope so that** $\beta = 20°$**.**

By way of example, at Ismenius Cavus for a τ factor of 0.4 and an areocentric longitude L_s of $270°$, descending a $30°$ slope bearing North results in a daily insolation of $319\,\mathrm{Whm}^{-2}$. This is increased to $767\,\mathrm{Whm}^{-2}$ 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 $1046\,\mathrm{Whm}^{-2}$ with $\beta = 20°$. The solar power generated from this scenario is simulated. Figure 10 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 $25\,\mathrm{s}$ and $35\,\mathrm{s}$ which worsen solar power output by changing the SA surface inclination angle from $\sim 30°$ to $\sim 40°$. Four separate $5°$ backward pitch decrements are executed from $45\,\mathrm{s}$ to $65\,\mathrm{s}$, progressively improving power generation as β is decreased from $\sim 40°$ to $\sim 20°$. 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.

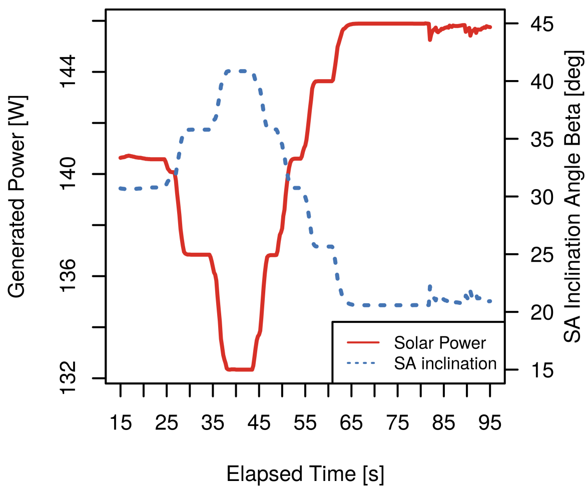


Figure 10: Slope compensation with active suspension system to reduce the SA surface inclination angle. Slope inclination angle $B = 30°$. In (a), $\beta = B = 30°$. In (b), the rover is tilted $10°$ in the opposite direction of the slope so that $\beta = 20°$.

5. Conclusion

The findings of this thesis 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. In light of this, SA sizing for the the worst case daily insolations introduce 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) Conducting a power budget cost-benefit analysis with respect to the power draws from the suspensions systems motors that are required to obtain the sun-facing inclined SA surfaces power gains.
(2) Achieving higher pitch and rolls angles so that higher SA surface inclination angles may be attained.
(3) Simulating ground adaption scenarios that preserve a desired SA surface position into a fixed plane.
(4) Simulating shadowing events on the SA and analyzing their affect on power outputs, in particular for shadows caused by the RA.
(5) Implementing a battery model to simulate battery charge and discharge for a more complete power subsystem simulation.
(6) Developing power budgets for onboard instruments to simulate scenarios such as drilling for sample return missions.
(7) Proposing SherpaTT SA designs for terrestrial and lunar mission scenarios.
(8) Exploring other alternative use cases for the rover's active suspension system such as nighttime star tracking for astronomical observations with a mounted telescope.

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