Overachieving in Hell: a Novel and Durable 3 Input Mechanical Navigation System for Venus Surface Operation

By: TCHS Science Research Club, LCHS Engineering Club

Short description (140 characters)
Provide a brief description of your idea. Be clear and concise.

A 3 output pin system uses 2 pendulums for attitude, a bumper for rocks, and an idler for holes. A Sweet CP mech. allows for binary output.

Please describe, in a non-confidential way, the operation of your sensor. *

To facilitate terrain mapping, a set of 8 wheels will extend in front of the rover, each on the end of their own titanium arm. If the arm moves down by an angle of >25°, it will generate a positive read, signaling to the rover that there is an obstacle. There will be three arms placed in front of each front wheel and one additional arm mounted in between the two wheels. This will allow the rover to detect any holes wider than 0.1m under the wheels and any hole wider than 0.5m under the rover. To allow independent movement, each arm will be mounted on a concentric axle with a pin which will allow individual actuation of each arm. The pin on each arm will rest in a channel in a cam plate, which allows it to push the cam plate clockwise and prevent counterclockwise motion. Thus, the wheels will be able to freely move upwards and over rocks without triggering the mechanism. The cam plate will mesh with two tabs at the bottom of a transmission plate. This will translate the rotational motion of the arms and detection wheels into a linear motion. Specifically, a 25° rotation will result in a 3cm lateral motion. The transmission plate will be mated to a conversion mechanism described later, which mates with the input pin. To prevent excessive movement, a stopper will be paired with a channel in the transmission plate, which will prevent lateral movement greater than 3cm. This will help to avoid mechanical wear and damage of the parts. All mechanisms, aside from the arms, will be mounted in a housing protecting them from environmental stress and allowing the parts to function as intended.

To detect rocks we will use a simple bumper extending 2 ft in front of the rover. The bumper will interact with the transmission plate (described above) through a channel in the back. When pushed in, the bumper will push the transmission plate the same distance, which activates the pin. In addition to the stopper on the plate, the bumper will have a stopper to prevent excessive plate movement (>3cm). In addition, the bumper will feature two rails that extend anteriorly, which slides into corresponding channels in the housing. This will reduce the stress on the transmission plate and ensure proper linear actuation. To restore the transmission plate back to the neutral position, a compression spring will be mounted between the channel of the transmission plate and the stopper in the housing. To prevent conflicting motions between the two components, the pins that attach to the CAM plates and the bumper are only touching each other and not welded together. This allows each detector to move independently while still driving a single input pin.

To detect rover attitude in pitch and roll, two pendulums will give feedback if the rover is tilted ≥30 degrees at any given time. To elaborate, the pendulum is attached to a lemniscate cam plate which will translate its arc path into a linear path. The plate will be attached to an output shaft encased in a linear bearing in order to ensure linear actuation. As the rover's Angle of Attack fluctuates, the pendulum will rotate due to gravity, thus rotating the cam plate. Cam plate rotation will cause linkage between the plate and the output pin shift, pushing the output pin. This mechanism will also be encased to protect from environmental stress.

Moreover, by employing two separate pendulums, the rover can detect pitch and roll to determine whether the area is traversable. The pendulum design will also be able to detect the pure angle of the slope instead of the angle relative to the rover, a potential issue while traversing gradual slopes. The doorknob hole detector, bumper, and pendulum will be attached to a special binary conversion mechanism.

The conversion mechanism allows for the elimination of partial extension of the pin; converting a never-ending linear sensor position to a "yes" or "no" for rover in the form of the 25N 3cm output pin movement.

Please describe how your sensor is suitable for the operational environment on Venus. Consider describing how your sensor design will cope with high temperatures, high atmospheric pressure, wind, launch vibrations, etc while in operation *

The sensing package was designed from the beginning to be able to exceed the operational parameters in terms of both structural integrity and mechanical/chemical wear. The overall material choices made prioritized longevity over all else, and are predicted by the literature to allow for a functional lifespan well exceeding one year of exposure. A combination of ceramic, titanium, 310 steel, and coated tungsten were used to allow each subsystem to remain lightweight while avoiding chemical attack and mechanical degradation.

In terms of mechanical durability and testing, 4 rounds of computational design refinement were completed on each part, beginning with Finite element analysis under the operating conditions and ending with the topology optimization and finalization of the parts. This process thoroughly checked our system's durability in extremely high load environments (2x to 5x expected loads tested) to ensure that such a sensor would have a more than suitable lifespan on the surface of Venus.

The main load bearing components, especially in the terrain mapping subsystem, which directly contacts the surface, were simulated in conditions doubling or tripling their operating loads, including gravity. For this task ANSYS Fluent was set up to perform structural finite element analysis on the main load bearing parts, solving for Von Mises stress and displacement.

The bumper, which contacts surface terrain with up to 30N of force before actuating a signal, was tested with 150N of collision force, the maximum the rover is capable of, in a 1.12G environment. Flexing was minimal and there was no stress buildup noted.

The wheel arm, which rolls along the terrain to detect holes, encounters 20N tangent loadings during regular operation. During testing it was simulated with a 50N loading. Stress buildup was noted in some sharp corners, which informed a geometry change in the part, smoothing out topographical transitions to minimize mechanical stress concentration. By adding material around the joint and lengthening the part, the stress hotspots were corrected.

The internals of the pendulum also experience high loadings, due to the manipulation of the coated tungsten weight. The main load bearing parts which connect to the weight and cam plate inside of the pendulum are the weight stem, which connects the tungsten to the cam plate, and the pushrod, which transmits force from the cam plate into the binary converter mechanism.

The weight stem was simulated at 50N tangential loading, about 2.5x the expected operating load, and performed well even with the initial topography. The smooth transition between connectors and the titanium rod prevented any stress hotspots even under extremely high loadings.

The pushrod, which has an operational loading of 25N as it actuates the binary converter, also performed well under 2x the expected compression loading, with no stress concentration points noted.

The Finite Element analysis design process either leaves parts the same mass (if they have no problems), or increases their mass to alleviate mechanical problems discovered through the process. Thus after the two rounds of stress based refinement, the parts were fed into topology optimization algorithms, which worked to trim off as much unnecessary material as possible, while still minimizing strain and part compliance. The mass savings goals were 50% for all parts, under the same amplified loading conditions that the mechanical simulations were conducted in.

The front bumper was discovered to be over reinforced, with several extra kilograms of metal able to be removed from the bulky bottom plate. The reinforcing ribs were more than enough to support central and asymmetric loadings, providing rigidity even when contacting rocks at the very edge of the bumper.

The wheel arm was found to be needlessly solid, prompting a switch to hollow beams, also saving several kilograms in otherwise useless mass.

The pendulum parts both have high large material surpluses on the weight attachment point and the central part of the pushrod. This material was removed.

Because topographically optimized geometries are not easily manufactured through classical subtractive techniques, the information on which material was not structurally important was used by the design team to cut out metal in a more pragmatic way, allowing these computational weight savings to translate to real world weight savings.

Thus our combination of vigorous material vetting, finite element analysis, and topology optimization ensure a mechanism which is 2-3x stronger than it needs to be for long term Venetian operation for years at a time.

Please describe the materials you anticipate needing for constructing the sensor. *

The high temperature and crushing atmospheric pressure make it nearly impossible for rovers to explore the surface of Venus for prolonged periods of time. However, with durable materials resistant to the environment, rovers can survive for longer, collecting ever valuable long-term longitudinal data. Taking this into consideration, a rover's mechanical sensor has to last as long, if not longer, than its respective rover.

Several factors helped determine optimal materials to use in sensor construction. In addition to being resistant to Venus's physical and chemical attacks, the materials must survive heavy winds, launch vibrations, and passage through space. Material properties also determine sensor longevity. For these reasons, 310 stainless steel, Ti-6-4, SiC, and tungsten are the most suitable materials to build a long-lasting, functional sensor.

Sulfuric acid rains and trace HCl and HF gases are prevalent on Venus. Despite the seemingly durable 304 stainless, 310 stainless proved superior in acid corrosion resistance, especially in highly reducing environments with constant exposure to chlorides and sulfuric acids. Due to its high Cr and moderate Ni content, 310 stainless is more resistant to sulfidation. Moreover, the low carbon versions of austenitic stainless steel, such as 304, have reduced creep strength at higher temperatures and are more susceptible to distortion over time. Thus, 304 stainless is not suitable for use.

The choice between 310 stainless and titanium was disputed. However, Ti alloys are less corrosion, chemical, and heat resistant than 310. They are somewhat corrosion resistant but can be susceptible to pitting and crevice attacks at temperatures higher than 70°C. Crevice corrosion is reported to have occurred in chloride, fluoride, or sulfate-containing solutions, rendering it undesirable in externally exposed arms, frames, and structural components. Ti alloys have poor abrasion resistance due to thin surface oxide layers, requiring heavy anodization coatings. However, coated Ti-6-4 alloys may be helpful in internal mechanisms due to their lightweight nature. A heavy anodization coating will protect Ti-6-4 parts from physical and chemical stress, as seen in the CAM plate design.

Anodization is an electrochemical process that gives metal surfaces a durable, abrasion and corrosion resistant finish, keeping metallic surfaces from welding upon contact. To prevent cold welding in space, these techniques can be used to cover the sensor's uncoated metallic components. A thicker film of oxidized metal is suggested to ensure the anodized layer will not be scratched off unknowingly.

Another possible issue was carburization, a process in which steel absorbs carbon when heated in the presence of CO. The increased carbon levels in carburized steel lead to embrittlement, which can lead to various forms of fracture. However, there are no reports of CO presence in Venus' atmosphere, and gas carburization typically occurs at 900-950°C, well outside the temperature range of Venus.

Sigma phase embrittlement was also a potential problem. Sigma phase is a detrimental phase of stainless steel that exhibits severe loss of toughness and corrosion resistance, resulting in cracking and component failure. Prolonged exposure to high temperatures causes Cr depletion from grain boundaries, inducing heavy intergranular corrosion. Fortunately, the temperature range on Venus does not allow this to occur, making 310 stainless safe to use.

Chemical reactivity determined which materials would be suitable for use. The atmosphere of Venus contains 96.5% CO_2, 3.5% N_2, and trace gases, most notably HCl, HF, and H_2SO_4. 310 stainless, TI-64, SiC, and tungsten do not react with these gases in the high temperature and pressure environment of Venus (462°C and 93 bar).

Chemical vapor deposition can be used to coat select internal parts with a SiC film, reducing wear and abrasion. The usage of SiC instead of Si_3N_4 for CVD coatings rests on the fact that performing CVD with

Si_3N_4 results in hydrogen bubble formation. Upon bursting, these bubbles leave cracks in the coat, exposing the underlying material and accelerating deterioration. Because CVD will be used to coat parts subject to constant contact, the internal mechanism will succumb to mechanical wear without it. To ensure longevity, parts of the binary conversion mechanism must be coated in SiC.
SiC is known for its resistance to corrosion, abrasion, erosion, and mechanical wear. It can be used as a very effective coating, shielding underlying material from acid attacks and high temperatures. Although SiC is difficult to mill, it offers the best heat and corrosion resistance of all ceramic materials, crucial to the sensor's operational longevity.
Due to its mass, tungsten is a suitable material to be used as weights for the CAM pendulum. In addition to its ability to retain its shape and strength, tungsten has excellent chemical resistance to HCl, HF, and H_2SO_4 acid attacks.

Please describe the electrical power requirements of your sensor. Describe what electrical components are included in your sensor and why. If none, please indicate "Not applicable".

Not applicable

Please describe how your proposed sensor will trigger the pin(s). *

The three different subsystems on the rover measure terrain navigability, roll angle, and pitch angle. The mechanical inputs from these mechanisms is by definition analog in terms of the linear position of the input pin; the position of the pendulum input rod can be in any position on its bearing, not just 0 or 1 extension points. Thus, to give the rover a consistent 3cm 25N output upon an obstacle, this constantly changing analog signal must be reduced to a "go/no go" digital signal.

To accomplish this we use a mechanical binary converter, composed of an internal spring package and a casing. The spring casing is composed of two constant force springs, which force an actuation pin out, forcing the package to lengthen inside of the casing.
At rest, the actuation pin is seated against the sloped wall of the casing, but when the asymmetric input pin is moved, it forces the spring package to slope up against the wall, bringing the actuation pin closer to the output hole. Once the linear input pin from the external sensor is forced past its threshold, the spring package slots in with the output hole, and the potential energy stored during the partial analog phase of input is used to push the actuation pin (which pushes the output pin) with 25N of force exactly 3cm; thus creating a mechanical binary input.

Note that the spring package uses pre tensioned constant force steel springs, which will provide a constant 25N force throughout the entire pin stroke.

Please describe how your sensor meets the physical constraints of the current rover design (i.e. assembled of environmentally appropriate materials, mass ≤ 25kg, not more than 1m from rover body, not more than 0.875m off the surface) *
As discussed before, the materials used in the rover were deliberately chosen to withstand the chemical environment of Venus. The front assembly is the largest part, extending 0.6m out in front of the rover, but

well within the requirements. The bumper plate is the tallest component, rising 0.35m above the ground, also within the operating window. The two pendulums for pitch and roll are mounted on the rover side and rear, and are low profile enough that they do not present any challenge to the volume requirements, neatly tucked in between the wheels.
Thus our sensor system satisfies all of the given physical requirements with room to spare.

CITATIONS

1. 2002, W. by A. Z. M. J. 8. (2018, August 17). Stainless Steel - High Temperature Resistance. Retrieved May 18, 2020, from https://www.azom.com/article.aspx?ArticleID=1175
2. Alloy 304/304L Austenitic Stainless Steel Plate. (n.d.). Retrieved May 16, 2020, from https://www.sandmeyersteel.com/304L.html#CorrosionResistance
3. Alloy 310/310S Heat Resistant Stainless Steel Plate. (n.d.). Retrieved April 15, 2020, from https://www.sandmeyersteel.com/310-310S.html#CorrosionResistance
4. Carburization. (n.d.). Retrieved May 24, 2020, from https://www.sciencedirect.com/topics/materials-science/carburization
5. CERAMIC BEARINGS. (n.d.). Retrieved May 15, 2020, from https://koyo.jtekt.co.jp/en/assets/file/pdf/catb1013ex.pdf
6. Ceramic Materials Their Properties Part 2. (n.d.). Retrieved May 25, 2020, from https://www.carterbearings.co.uk/unasis/hybrid-and-ceramic-bearings/ceramic-matericals-and-their-properties-part-2/
7. Danielsson, Ö. (2002). Simulations of Silicon Carbide Chemical Vapor Deposition. Retrieved May 27, 2020, from http://www.diva-portal.org/smash/get/diva2:697853/FULLTEXT02.pdf
8. Iron Alloy. (n.d.). Retrieved May 20, 2020, from https://www.makeitfrom.com/compare/AISI-310-S31000-Stainless-Steel/Annealed-304-Stainless-Steel
9. Pedersen, H. (2008). Chloride-based Silicon Carbide CVD. Retrieved May 28, 2020, from https://www.diva-portal.org/smash/get/diva2:114173/FULLTEXT01.pdf
10. Powell, J. A., Petit, J. B., & Matus, L. G. (n.d.). Advances in silicon carbide Chemical Vapor Deposition (CVD) for semiconductor device fabrication. Retrieved May 28, 2020, from https://ntrs.nasa.gov/search.jsp?R=19910014633

11. Prando, D., Brenna, A., Diamanti, M. V., Beretta, S., Bolzoni, F., Ormellese, M., & Pedeferri, M. P. (n.d.). Corrosion of Titanium: Part 1: Aggressive Environments and Main Forms of Degradation. (2017). Retrieved May 20, 2020, from https://journals.sagepub.com/doi/full/10.5301/jabfm.5000387
12. Ratnayake, D., Martin, M. D., Gowrishetty, U. R., Porter, D. A., Berfield, T. A., McNamara, S. P., & Walsh, K. M. (2015). Engineering stress in thin films for the field of bistable MEMS. Retrieved May 16, 2020, from https://iopscience.iop.org/article/10.1088/0960-1317/25/12/125025/ampdf
13. SiC 3 - Silicon Carbide Coating. (2019, October 23). Retrieved May 26, 2020, from https://www.thermic-edge.com/sic-3/
14. Titanium. (2019, August 16). Retrieved May 18, 2020 from https://www.britannica.com/science/titanium
15. Titanium Alloys - Wear Resistance. (3n.d., January 2002). Retrieved May 20, 2020, from https://www.carterbearings.co.uk/unasis/hybrid-and-ceramic-bearings/ceramic-matericals-and-their-properties-part-2/
16. Titanium corrosion. (n.d.). Retrieved May 18, 2020, from https://corrosion-doctors.org/MatSelect/corrtitanium.htm
17. Vyas, K. (2019, September 3). Cold Welding: Joining Metals Without Heat. Retrieved May 21, 2020, from https://interestingengineering.com/cold-welding-joining-metals-without-heat