CHALLENGES OF DESIGNING A PASSIVE THERMAL CONTROL SYSTEM FOR THE ASTROBOTIC PEREGRINE LUNAR LANDER

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ABSTRACT

The Astrobotic Peregrine is a lunar lander currently undergoing design by Astrobotic Technology with help from NASA through the Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) program. This paper will discuss the challenges of designing a passive thermal control system for the lander, and how the design has evolved from the initial passive concept. These challenges include drastically varying worst hot and worst cold case thermal environments, narrow temperature limits of critical components, limited available locations for spacecraft component mounting, and unexpected changes causing significant thermal impacts. The initial thermal control strategy was to cold bias the spacecraft by thermally coupling all spacecraft components to one mounting deck, which also doubled as a radiator, and using heaters to maintain each component's temperature above its lower temperature limit when in the cold environments. As the design evolved, this strategy alone became inadequate. As heat dissipations increased and became more varying with the addition of components, the thermal design was changed and additional thermal control technologies added. Thermal control strategies incorporated into the design include dictating the lander orientation in demanding environments, defining locations for critical spacecraft components, limiting component operation when possible, and using technology to create variable thermal contacts. Additional design changes will occur as the design continues to evolve to optimize the most effective thermal control system. The thermal design of Peregrine is still in progress, with Critical Design Review (CDR) scheduled for December 2019.

NOMENCLATURE

α	Solar Absorptivity
ACT	Advanced Cooling Technologies
C	Celsius
CATALYST	Cargo Transportation and Landing by Soft Touchdown
CDR	Critical Design Review
CLPS	Commercial Lunar Payload Services
ε	Infrared Emissivity
IAU	Integrated Avionics Unit
IR	Infrared
JPL	Jet Propulsion Laboratory
LIDAR	Light Detection and Ranging

m	Meters
M1	Mission 1
MLI	Multilayer Insulation
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
RF	Radio Frequency
SAA	Space Act Agreement
TD	Thermal Desktop
VCHP	Variable Conductance Heat Pipe
W	Watts

BACKGROUND

Astrobotic

Astrobotic Technology, Inc. is a space robotics company founded in 2008 that began working with NASA in 2014 as part of the Lunar CATALYST project. Through the Lunar CATALYST initiative, NASA competitively selected three partners to galvanize commercial cargo transportation means to the surface of the Moon. Each of the companies has a no-funds-exchanged Space Act Agreement (SAA) partnership through which NASA works with the company to help develop their lunar lander capabilities with the goal of developing robotic lunar landers for integration with the United States commercial launch capabilities to deliver payloads to the lunar surface.[1] As part of the CATALYST project, engineers at NASA Marshall Space Flight Center conduct the majority of the thermal engineering work for Astrobotic Peregrine. The end of CATALYST is September 30, 2019.

In May 2019, NASA selected Astrobotic as one of the first three commercial Moon landing service providers that will deliver science and technology payloads under Commercial Lunar Payload Services (CLPS) as part of the Artemis program. Through CLPS, NASA awarded Astrobotic with $79.5 million to fly as many as 14 CLPS payloads to the Moon.[2]

Peregrine

Peregrine is the lunar lander being developed by Astrobotic throughout Lunar CATALYST, and the same lander that will deliver CLPS payloads to the moon. Mission 1 (M1) will launch in late June 2021, and land on the lunar surface by July 17, 2021. The lander is relatively small at about 1.9m high, 2.5m wide. **Error! Reference source not found.** shows the Thermal Desktop (TD) representation of Peregrine. The landing location is Lacus Mortis, at 43.9142°N, 25.1479°E, between 55 and 110 hours after lunar sunrise. The surface operation goal is to operate for 192 hours total (eight earth days), throughout the lunar day. The lander is not attempting to survive the lunar night for M1.

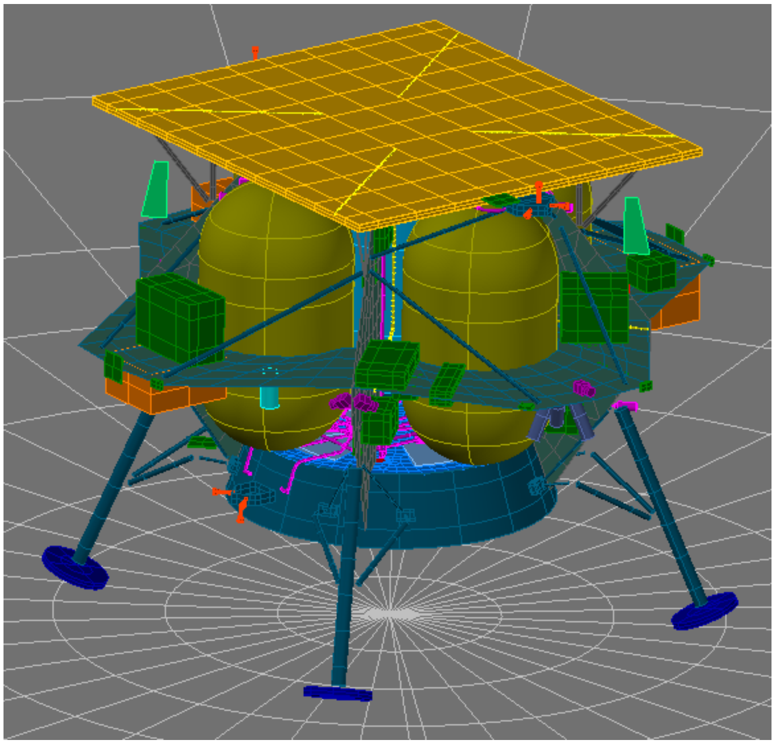

Figure 1: Peregrine Lunar Lander TD Model

THERMAL CHALLENGES

The thermal design and analysis of a lunar lander presents many interesting challenges and Peregrine is no exception. Some of the most apparent thermal challenges include drastically varying worst hot and worst cold case thermal environments, narrow temperature limits of critical components, limited available locations for spacecraft component mounting due to payload accommodations, and unexpected changes to lander subsystem designs.

Extreme Worst Hot and Worst Cold Case Environments

After landing on the moon, Peregrine will need to survive operation through eight earth days during the lunar day environment. The lander will touch down on the lunar surface between 55 and 110 hours after lunar sunrise, which means that the lander will experience the hottest part of the lunar day. The lunar day and lunar night thermal environments are dramatically different due to the negligible thermal conductivity of the regolith and the inability of the lunar surface to conduct or radiate sufficient heat to remain thermally stable throughout the lunar day. The moon also has very little atmosphere, which does not protect the surface from solar flux during the day or retain heat during the night. At roughly 45° latitude, the lunar day can be as hot as 76°C and the lunar night as cold as -190°C.[3] Even shadows on the moon have a large temperature drop from the adjacent area in the sunlight. Peregrine M1 is not planned to survive the lunar night because it is not designed to generate enough power to maintain minimum temperature limits of components through 14 earth days of a -190°C environment.

Peregrine's coldest environment is during the transit from earth to the moon, during which the solar panels maintain a solar inertial pointing, and so the bottom of the lander will always be facing away from the sun.

Narrow Temperature Limits of Critical Components

Narrow temperature limits of critical components are another thermal design challenge. One component in particular is the battery, which has allowable flight temperatures of 10°C to 35°C. Its high allowable cold temperature could mean that constant heaters are required, but its low allowable hot temperature could mean that it would need extra radiator surface area, depending on its heat dissipation. An added challenge with the battery is that it has a varying heat dissipation, depending on whether it is charging or discharging, and how much power it is supplying. As the design of the lander matures, the power needs mature, and the heat dissipation of the battery is constantly updating.

Limited Available Locations for Spacecraft Component Placement

Additionally, there is limited space on the lander to mount spacecraft critical components. One reason for this is simply because you cannot fly an unlimited amount of mass to the moon, but another reason is that much of Peregrine's deck space has been dedicated to unknown payloads. As a commercial company, Astrobotic generates revenue from selling rides to payloads, but many of the payload details were unknown during the design of the lander. This resulted in developing the thermal design while making assumptions about payloads, then providing thermal environment ranges and heat flow to the lander restrictions to the payloads. With the CLPS award, additional NASA payloads will take up space on the lander. This is not only a concern from a volume perspective, but also because placing many hot components next to each other could cause overheating.

Unexpected Changes

Unexpected changes always serve as an additional challenge on engineering projects. A few unexpected changes that have required updates to the thermal design include upgrading to a transponder that dissipates more than four times the heat of the previous transponder, and uncertain propellant temperature limits, as the engines are still in development.

INITIAL THERMAL CONTROL STRATEGY

The early thermal control design of Peregrine started as a simple passive design. The basic idea was to cold bias the spacecraft by thermally coupling all spacecraft components to one mounting deck, 'the avionics deck', which also doubled as a radiator. The deck has Silver Teflon Tape on the top ($\varepsilon=0.81$, $\alpha=0.08$) to facilitate dissipation of heat away from the lander, and multilayer insulation (MLI) on the bottom, to protect from reflected heat from the lunar surface during lunar surface operation. There is the option to add radiator surfaces if more heat needs dissipated. For this simple strategy, in the cold environment, heaters make up for heat lost through the radiator surfaces. This was a good starting point as it was a simple design, but it was inefficient because it was not power or mass conscious.

As the design evolved, this strategy alone became inadequate. As more components added more heat to the deck, additional radiator space and heater power were required. Different components on the avionics deck have different temperature limits, and keeping all of the components to the narrowest temperature limit was inefficient. Accordingly, the design required the relocation of several high heat dissipating components, and alternative thermal control technologies.

THERMAL CONTROL SOLUTIONS TO CHALLENGES

Many solutions to the challenges listed above were explored. Since the design is not yet final, it is possible that the current thermal control strategy will change as the lander increases in fidelity, and alternative solutions could become apparent. Some of the strategies currently used include dictating orientation of the lander, defining component locations, limiting component operation, and use of thermal control technology with variable thermal contact.

Dictating Lander Orientation

Because Peregrine will land on the lunar surface at a latitude of about 45° north, the different sides of the lander see different amounts of sunlight and so experience different thermal environments. One of the early design decisions was to orient the lander on the surface so that the avionics deck faced north. This keeps critical components necessary for surface operation, like the battery and Integrated Avionics Unit (IAU), on the coolest side of the lander, so that they do not overheat. Figure 2 shows the estimated temperatures of the lander and surface at Lunar Noon to demonstrate the different environments experienced by the different sides of the lander.

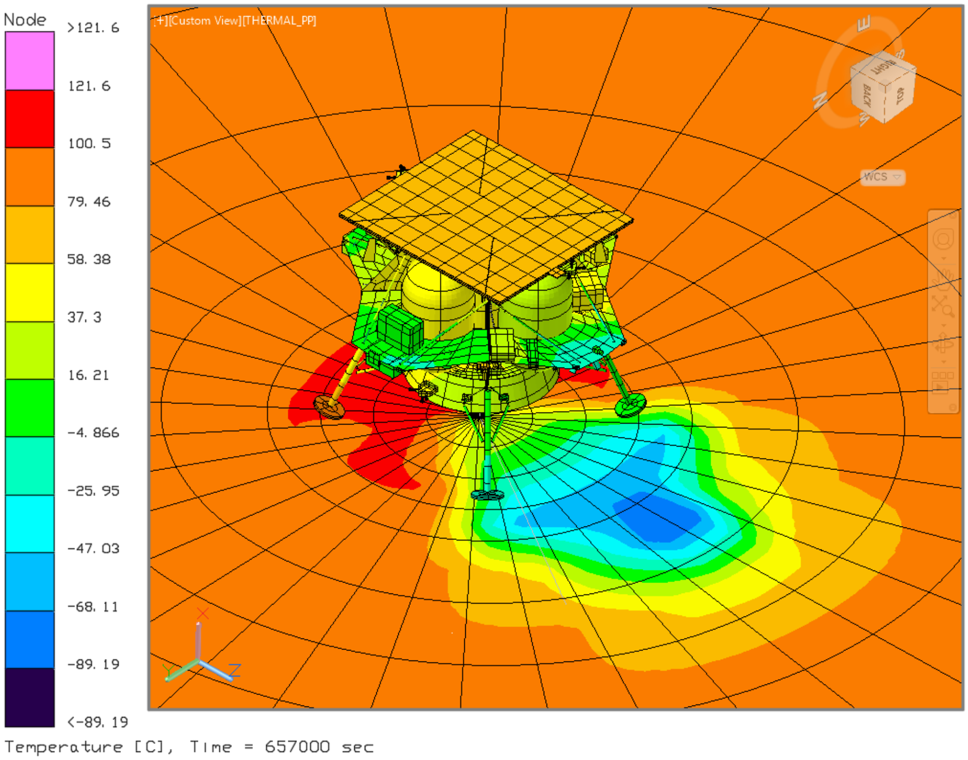

Figure 2: Lunar Surface Temperature Estimates at Lunar Noon

Defining Component Locations

Along with defining the orientation of the lander, it was also necessary to define the location of several high heat dissipating components. Most of the critical spacecraft components mount to the avionics deck to be in the most thermally favorable position during lunar surface operations, but there are some exceptions. The Doppler Light Detection and Ranging (LIDAR) electronics box, for example, is a critical spacecraft component, and it dissipates a high amount of heat during its operation (80W). The difference between this component and other critical components is that it only operates during lunar descent and checkout periods in lunar orbit, and does not operate on the lunar surface. Because it is not important to maintain the Doppler Lidar temperatures on the surface, it does not mount to the avionics deck. This prevents it from overheating the other components during lunar descent, but puts it in a position where it is too hot to operate on the surface.

Limiting Component Operation

Another method that has been necessary to maintaining temperature limits of all components is limiting the operation of some of the electronics, both on an individual level and at the lander system level. For instance, the surface-to-ground transponder initially had several possible heat dissipation based on the level of Radio Frequency (RF) power output required for different phases of the mission. The higher the RF power output, the more data could be sent back to earth, but the higher the heat dissipation, and the hotter the transponder. To help maintain the transponder temperatures, it was thermally favorable to use a lower RF output during surface operations when the transponder is experiencing its hottest environment of the mission.

Similarly, after landing on the lunar surface, the thermal environment increases in temperature as lunar noon approaches, and then decreases in temperature as time progresses toward lunar night, and so there is the option for the lander to take a “siesta” during the hottest part of the lunar day. Peregrine’s mission is to operate for eight earth days on the surface, but it is not required to be continuous operation. That would allow time for a 24-hour siesta, during which the lander powers down to prevent overheating of critical components, when the environment is the hottest for critical components.

Thermal Control Technology with Variable Thermal Contact

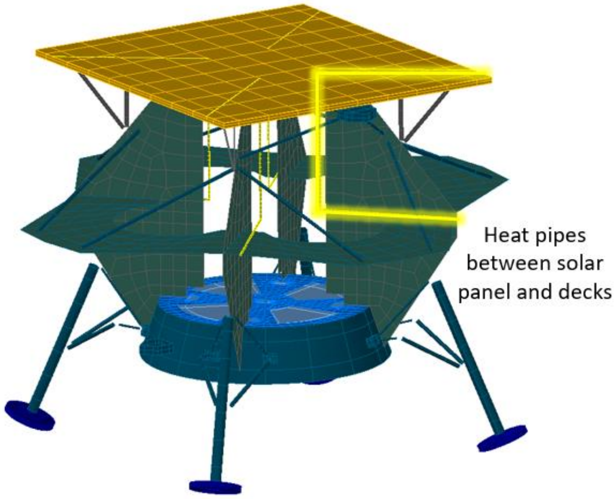

Figure 3: TD Model of Peregrine Highlighting Heat Pipes

The thermal subsystem has also been able to make use of several different types of technology that provide a variable thermal contact. The variable contact is key because of the varying environments. Diode heat pipes create a thermal path from the solar panel to the avionics deck and the deck opposite. This both cools the solar panel and provides heat to the avionics deck. Most importantly, it warms the battery, which has a low temperature limit of just 10°C and this saves heater power. It is necessary to use a diode heat pipe so that heat is only flowing in one direction: from the solar panel to the deck. Otherwise, when Peregrine is in the moon’s eclipse during orbit and the solar panel is facing the dark surface of the moon and is cold, heat would be transferred from the avionics deck to the solar panel, which would make the electronics on the deck too cold. These heat pipes are only useful during transit and orbit because a section of the pipe is vertical and the lunar gravity prevents it from operating on the surface. Although unavoidable, this is also helpful because the deck receives more heating from the sunlight on the surface than in the other environments, and does not need the added heat from the solar panel. Figure 3 shows the Thermal Desktop model of Peregrine with heat pipes shown in yellow, with one heat pipe highlighted.

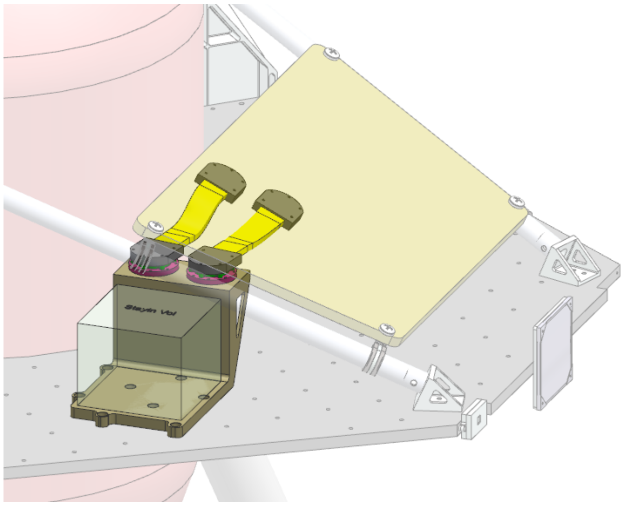

Figure 4: Thermal Switch System

Another piece of technology integrated into the design is a thermal switch to use between the transponder and a radiator. The transponder dissipates a varying amount of heat in different phases. During transit and orbit, it alternates dissipating 54W for four hours and 7W for four hours, then during a roughly 90 minute descent period it dissipates a constant 126W, and finally in the hot environment of the lunar surface, it dissipates a continuous 54W. Rather than a permanent contact to a radiator, which would require a higher amount of heater power during its low heat dissipating phases, a thermal switch is used. When the transponder reaches a defined high temperature, the thermal switch enables a 0.9 W/°C contact between the transponder and the radiator, to allow the transponder to radiate excess heat. When the transponder reaches a defined low temperature, the thermal switch contact reduces to 0.002 W/°C to prevent the transponder from dissipating away too much heat. Figure 4 shows the current concept for the thermal switching system, which is being developed at NASA Jet Propulsion Laboratory (JPL).

Also under consideration are an advanced variable conductance heat pipe (VCHP) and a loop heat pipe (LHP) that are both currently being developed by Advanced Control Technologies, Inc. (ACT). Assessment of if these devices will enhance the thermal control design for Peregrine is ongoing. The VCHP could be used as a variable contact between the transponder and its radiator, in conjunction with the thermal switch detailed above. The switch enables the transponder to operate at its current RF output, but the VCHP would offer an additional path of heat rejection to allow the transponder to operate at a higher RF output. The LHP could be used between the avionics deck, beneath high heat dissipating components, and an adjacent deck to spread the heat between the avionics deck and a cooler deck during lunar surface operations.

CONCLUSIONS

The Astrobotic Peregrine Lunar Lander will deliver payloads to the lunar surface by July 2021. Determining solutions for several thermal control challenges has contributed to making that a reality. Some of these challenges found throughout the design process include extreme worst hot and worst cold case thermal environments, narrow temperature limits of critical components, limited available locations for spacecraft critical components due to designated payload space, and unexpected changes to other subsystems. Thermal control strategies that have proven useful in the design and analysis of the lander have included dictating the lander orientation in the most thermally unfavorable environments, defining component location for critical spacecraft components, limiting component operation when possible, and using technology to create variable thermal contacts. As the lander design continues to evolve, the thermal control system design will likely continue to change, as well.

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Alex Szerszen's descent environment modeling greatly contributed to the Peregrine thermal design and analysis efforts. To learn more about his work, you can read his paper: TFAWS-19-PT-11, 'Thermal Environment Modeling Practices for the Descent Trajectory of Lunar Landers'.

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REFERENCES

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[1] Mahoney, Erin. "Lunar CATALYST." NASA. 17 Dec. 2015. NASA. <https://www.nasa.gov/lunarcatalyst/>.

[2] Daines, Gary. "Commercial Lunar Payload Services." NASA. 14 Mar. 2019. NASA. <https://www.nasa.gov/content/commercial-lunar-payload-services>.

[3] Paige, David. "LRO Diviner Lunar Radiometer Experiment." Diviner. 2019. UCLA. 02 July 2019 <https://www.diviner.ucla.edu/science>.