Thermal Control Architecture for a Planetary and Lunar Surface Exploration Micro-Robot

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Abstract. A thermal control architecture design study is conducted for a novel robotic planetary and lunar surface exploration concept. The concept is based on the deployment of a large number of small spherical mobile robots over large areas, which employ hopping, bouncing and rolling as means of locomotion. The aim of the research is to prevent freezing and overheating of the robots, without compromising their mechanical and thermal reliability and stability. The proposed thermal control architecture relies on a low emissive silver surface coating and a low conductive silica aerogel insulation layer. This enables a single design to be used for several important potential explorations. The effects of a thermal control heat rejection mechanism, composed of a variable emittance coating and heat switch, are also studied in order to increase mission flexibility.

Keywords: Thermal design, thermal control, micro-robot, variable emittance coating, heat switch, space technology.
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INTRODUCTION

A new concept for planetary exploration, based on the deployment of a large number (hundreds to thousands) of small spherical mobile robots over large areas of a planet or moon's surface and subsurface, is being investigated by Dubowsky et al. (2005). This concept would enable the large-scale exploration survey of scientifically interesting properties, and mapping of the surface and caves of the body. The approach is an important potential alternative to current rover and lander-based planetary exploration, which is limited to studying small areas of a body's surface. Challenging environments, such as icy terrain on polar Mars and various gas giant moons, rough and high vertical relief landscape, and caves or other subsurface access (Boston, 2003) can so be explored.

The focus of this paper is on the thermal control architecture design of these exploration robots, to enable autonomous operation in harsh space mission conditions without risking freezing or overheating that would damage robot components (Swanson and Birur, 2003).

SYSTEM DESCRIPTION

The exploration robot is a self-contained spherical robot equipped with power and communication systems, a mobility system that enables it to move via hopping, rolling and bouncing, and a suite of miniaturized sensors such as imagers, and sensors for chemical analysis. Once developed, robot units can be custom-tailored to specific missions. A first conceptual design is seen in Figure 1.

Combined hopping, rolling and bouncing, results in an effective mobility mechanism for small devices in low gravity. This locomotion mode will allow the robots to travel through extremely rough terrain and access sites of interest that are beyond the reach of ordinary rovers and orbital or aerial platforms.

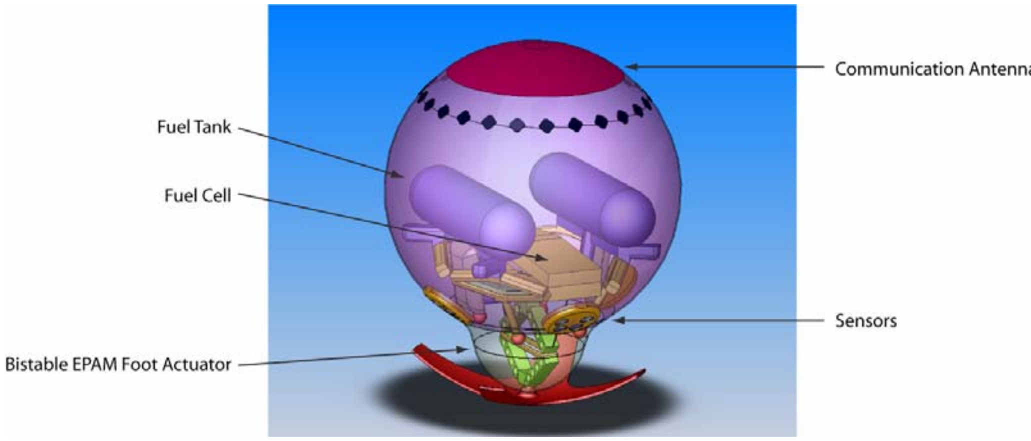

FIGURE 1. Conceptual Design of Exploration Robot with Its Foot Extended.

Basic robot mobility is provided by a bistable mechanism activated by dielectric elastomer actuators, also known as electroactive polymer muscle (EPAM) actuators. The device allows the flow of energy into the actuator over a period of seconds or minutes that is then continuous over a short high power stroke. EPAMs have shown potential, have good efficiency, low cost, and are lightweight and inherently simple. The actuator operating principle is based on the Maxwell (electrostatic) pressure, generated by a strong electric field applied across a soft elastomeric material. The bistable mechanism enables the robots to achieve mobility via directed hopping and they are weighted so that after one locomotion cycle of hopping, rolling and bouncing they will return to a posture with their “foot” on the ground.

The units will be powered by miniaturized fuel cells currently being developed at O'Hayre et al. (2003). Fuel cells were selected for this system as the balls lack the surface area for conventional photo-voltaic cells currently used on planetary missions. Additionally, solar cells would obviously not be useful for cave missions. Analyses have shown that fuel cell powered robots offer significant mass reduction advantages for long-range missions over similar battery powered units (Dubowsky et al., 2005). The use of bistable mechanisms for the EPAM actuators, which lowers peak power consumption necessary for hopping, makes the use of high efficiency – low power devices such as fuel cells feasible.

Sensors are the heart of the exploration robots as they perform the scientific exploration. They will be tailored to specific mission objectives. The robots will also require sensors for navigation, localization and locomotion, such as IMU’s. All sensors will be implemented by MEMS, to achieve the low size, weight, cost and power consumption objective of the concept.

Science data will be transmitted via low-power communication to a lander platform or an orbiting spacecraft, which then relays the data to Earth. Individual robots will cooperate semi-autonomously to share information, collaboratively explore science targets and relay commands and data in caves. Individual robots will form a local area network (LAN) to allow communication by a low-power transmission/receiver system.

THERMAL DESIGN FRAMEWORK

A robot’s thermal control design must be based upon the conditions presented by its mission. The specific missions for the proposed robots have yet to be selected. However, the range of potential mission targets for this concept can be narrowed based on factors such as surface temperature, atmospheric pressure, gravitational acceleration, scientific interest, and so on. As a result of a preliminary study, only planets and moons of the solar system made up of a solid surface, without a dense atmosphere, are candidates. The Moon, Mars, Jupiter’s Galilean moons (Io, Europa, Ganymede and Callisto), and Saturn’s moon Titan appear to be high on the list of potential mission targets. The present study is based on conditions representative of those bodies.

Design Requirements

The harsh space environment and unusual life cycle of this space exploration robot leads to some very challenging constraints in its thermal design process. First among these is the need to minimize heat loss while the robot is not active in cold environments because the amount of fuel aboard each robot is limited. Fuel consumption for heating purposes would reduce the robot's operating lifespan.

Second, to guarantee continuous operation of the robots, an active thermal control must be provided to prevent the possibility of overheating during activity use when the fuel cells will be producing electricity to power the robot's explorations. The fuel cells have a relatively low efficiency, resulting in considerable waste heat. Overheating may occur if robots are highly insulted to limit external heat loss when they are not active. The robot body temperature needs to be controlled either by adjusting levels of activity to limit the heat load or manipulating the heat loss rate. This is achieved here using a controlled heat rejection mechanism, which is designed so as to require as little external energy input as possible.

Finally, the thermal design architecture must be very robust. It is assumed that the internal temperature must be held to the range of ±50ºC, in order to guarantee operation of the electronic components. This requires effective thermal insulation, which limits the effects from external influences, and it leads to the minimization of stresses imposed on components resulting from different material thermal expansion coefficients. The latter is intended to ensure the mechanical structure's durability.

System Thermal Design

The thermal design is based upon minimizing heat loss through a combination of insulation and minimally radiating surfaces in combination with an actively controlled heat rejection mechanism. This allows the heat loss to be minimized except during heavy operation when excessive waste heat from the fuel cell must be rejected.

Owing to the low or very low atmospheric pressures on the candidate moons and planets, thermal radiation will often be the major source of heat loss. This loss may be limited by employing low emissivity surface finishes for external facings, as well as for the internal components. Surface coatings may reach emissivity values as low as 0.01 (for silver); silver or gold coatings have previously proven to be very effective in minimizing heat loss in space missions. Further, low emissivity coatings will often have low solar absorptivity, which helps reduce daytime heating of the robots.

In addition to the low emissivity external coating, a thick internal layer of insulation is required in order to limit temperature swings from the external environment. In particular, in the presence of a significant atmospheric pressure, the internal insulation layer limits convective heat losses.

Of all available insulation materials, silica aerogel claims one of the lowest thermal conductivities, with values of less than 0.02 W/(m·K). It also possesses the one of the lowest densities among solids ($\rho < 0.1$ g/cm^3) as a result of porosities ranging over 98% (Akimov, 2003). Aerogel is a solid substance, similar to a gel in which the liquid component is replaced with a gas. The present design is therefore based upon an aerogel insulating layer.

To control the body temperature of the robots without active modulation of the fuel cell heat generation, the external heat loss rate must also be controlled. Variable emittance coatings (VEC) are one way to influence radiative heat loss according to the exigencies. Two prototypes of this adaptive thermal control system, one based on micro-machined louver technology (Osiander et al., 2004) and the other on electrostatic switches (Biter, Oh, and Hess, 2002), were tested on NASA's *ST-5* spacecraft satellite mission, launched March 22, 2006. Other devices of the same purpose make use of electrochromic and electrophoretic technologies.

A further technique for controlling the heat loss rate is to introduce a "heat switch," which, when activated, will provide a low thermal resistance path for heat transfer from the interior to the robot's outside shell. Effectively, this switch shunts heat past the silica aerogel insulation layer. In practice, this switch might simple be a metallic rod which will connect with the outer surface when actuated. The excess heat is rejected either to the surface of the celestial body or the surrounding atmosphere. Because of the largely unknown celestial body thermal characteristics, including potentially very large variations in surface thermal conductivity between sites, interaction with the atmosphere is favored, as it is much more predictable. The robot's outer shell must be highly conductive in this case, to distribute all heat evenly around.

Desired properties of the thermal switch device are high thermal resistance at rest, high thermal conductance when activated and low power consumption. Additionally the switch must be small and low weight, possibly MEMS embedded. Several approaches exist to meet the requirements, such as paraffin and electrostatic actuated switches or passive bi-metal switches.

PERFORMANCE PREDICTIONS

The thermal model consists of a spherical shell, representing the robot, with a low emissivity outer coating and a thick inner insulation layer. Further it provides a contact area to the supporting surface and a homogeneous spherical body, which contains all components of a single robot. Variable emittance coatings on the shell and a heat switch are optional. Figure 2 shows a schematic drawing of the model including all heat transfer modes and thermal control provisions. More elaborate heat transfer models may be applied once the interior components of the robots are more clearly defined.

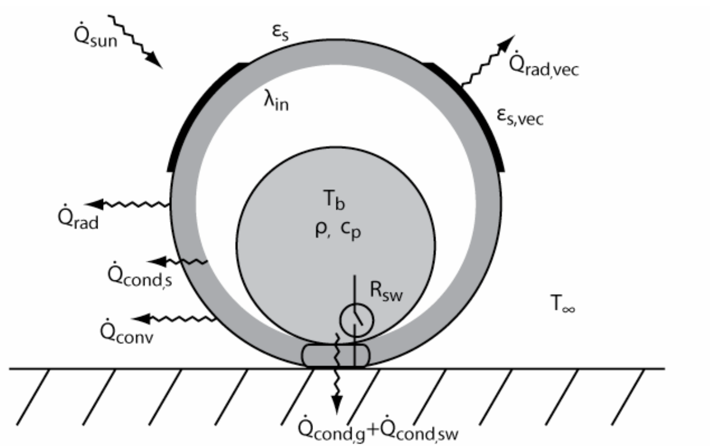

FIGURE 2. Schematic Drawing of Thermal Model.

Parametric Study

A parametric study was conducted to investigate the average heat loss of the micro-robots in various environments and to determine the requirements that thermal control components must fulfill in order avoid overheating during continuous operation. An identical robot design is used in each case to produce comparable results for all different situations. Table 1 regroups all fixed parameters relevant to the robot modeling.

TABLE 1. Fixed Robot Parameters for Thermal Simulations.

Parameter	Value
D (m)	0.1
m (kg)	0.1
D_b (m)	0.05
$(\rho\cdot c_p)_b$ (J/m$^3\cdot$K)	$3\cdot10^6$
x (mm)	25
λ_{in} (W/m·K)	0.005
ε_s	0.01
A_{cont} (m^2)	$1\cdot10^{-4}$
A_{vec}/A_s	0.75
$\dot{Q}_{fc}$ (W)	1
η_{fc}	0.65
η_{tot}	0.02

The environments considered consist mainly of celestial bodies without a notable atmosphere, as well as two separately treated environments representative of Mars and Titan. Both the latter have an atmosphere, and so convective heat losses are included in the respective calculations.

The primary goals of the study are to ensure that freezing and overheating of the robots is prevented. Two scenarios are used. A so-called passive-cold scenario simulates the robot maximum heat loss under a given environmental temperature T_∞ and constant body temperature (T_b = 300 K). These results are vital for consideration of freezing and minimization of heating. Results from this analysis include the maximum robot heat loss $\dot{Q}_{loss}$ and the corresponding shell surface temperature T_s (the latter being important for thermal stress considerations). The goal is to ensure as little as overall heat loss as possible without freezing, so as to increase the robot lifetime.

The second scenario, the so-called active-hot scenario, simulates the robot minimum heat loss under a given environmental temperature T_∞ and continuous operation. As this heat loss does not necessarily compensate for internal heat production, a thermal control mechanism must adjust the heat rejection rate, so that overheating is avoided. As a first step, the transient temperature increase of the robot body ΔT_b during a one-hour period is determined, assuming that the fuel cell is operating continuously at full capacity ($\dot{Q}_{heat,fc}$ = 0.98 W) and with no thermal control provision. As a second step, the effects of the modeled thermal control system are applied, and the thermal resistance of the heat switch R_{sw} and the emissivity of the variable emittance coating $\varepsilon_{s,vec}$, are varied.

Model Observations

Primary results of the parametric study are that robot freezing is avoided in all environments and that overheating can be prevented by the conceived thermal control mechanism under all circumstances.

For example, on Mars, a planet of high interest for robotic surface and subsurface exploration, both free and natural convection have to be taken into account in the passive-cold scenario simulation. The first simulates a cave situation and the second a case when robots are located on an open surface exposed to wind. In the carbon dioxide atmosphere wind speeds of up to 20 m/s are reached in surface areas (Kaplan, 1988). Table 2 summarizes the results. Details to the convection calculations can be found in Burg (2006).

TABLE 2. Mars Passive-Cold Scenario Simulation.

	Free Convection		**Forced Convection**	
T_∞ (K)	**$\dot{Q}_{loss}$ (W)**	**T_s (K)**	**$\dot{Q}_{loss}$ (W)**	**T_s (K)**
100	0.52	135	0.62	105
150	0.39	177	0.46	154
200	0.26	218	0.31	203
250	0.13	259	0.15	251

The effects of an active-hot scenario on body temperature and thermal control demands are illustrated under conditions lacking an atmosphere and not subjected to incoming solar radiation (such as in a cave) in Table 3.

TABLE 3. Active-Hot Scenario Simulation for Celestial Bodies without Notable Atmosphere and Solar Irradiation.

		Thermal Control Parameters	
T_∞ (K)	**ΔT_b (K)**	**R_{sw} (K/W)**	**$\varepsilon_{s,vec}$**
50	16	426	0.09
100	16	339	0.09
150	16	253	0.09
200	16	167	0.11
250	17	81	0.17

Beyond this, additional observations and conclusions are as follows: When convective heat losses are present in the system, they account for the majority of the heat loss. The effects of convection are however alleviated by the silica aerogel insulation layer inside the robot shell. The robot's surface temperature is reduced by the conductive thermal resistance and approaches the temperature of the surrounding environment.

Similarly, the silica aerogel insulation layer limits the radiative heat loss, even in the event the dust or other deposits on the exploration robots may increase surface emissivity values. This underlines the robustness of the thermal control architecture, and the comparative insensitivity of the design to modest variations in the surface emissivity when the heat switch is not active. When both thermal control mechanisms, the heat switch to shunt excess heat through the insulation layer and the variable emissivity coating to radiate it off, are active, effective thermal control is accomplished and adequate heat rejection is assured. In the event of convective heat loss, when the shell temperature drops close to ambient temperatures, thermal stress becomes an issue, as temperature differences of over 200 K may be occur between the robot shell and its body. This must be taken into account during the robot design phase.

The comparatively weak heat source of the robots, with respect to their thermal mass, induces a small temperature rise during the course of an hour-long continuous operation. This allows the thermal control system plenty of time to adapt to the new environment and so decreases the risk of overheating. Due to the small contact area between the exploration robots and their supporting surface, simulations have shown that conductive heat loss into the ground is very limited, even when the ground is modeled as a perfectly isothermal. In the present study, an upper-bound on conduction through the silica aerogel layer is examined because the interior surface temperature of the aerogel is set to the body temperature. Conduction loss is however notably reduced when providing the robot components with low emissive surface finishes and limiting fixture contacts. An additional radiation shield, comparable to a thermos bottle, is hereby potentially available.

With the proposed thermal design, essentially one uniform structure can be deployed on every mission location considered. Parallel missions, reducing development costs and increasing collected science data, could thus be conducted.

MISSION PROFILE

The estimated mechanical energy released per robot hop is 0.6 J. When considering the overall efficiency of the electrical power system, η_{tot} = 2%, a total energy of E_{jump}= 30 J must be released by the fuel to allow the robot to hop at the requested intensity. The bistable EPAM mechanism enables the actuator to be gradually charged and release the stored energy almost instantaneously at the moment of desire. With a fuel cell energy production of $\dot{Q}_{fc}$ = 1 W it takes 30 seconds to charge the bistable actuator. This is considered to be the maximum hopping rate of the robots and the graph of this function is seen in Figure 3 for an exemplary overall average heat loss rate of $\dot{Q}_{loss,av}$ = 0.2 W.

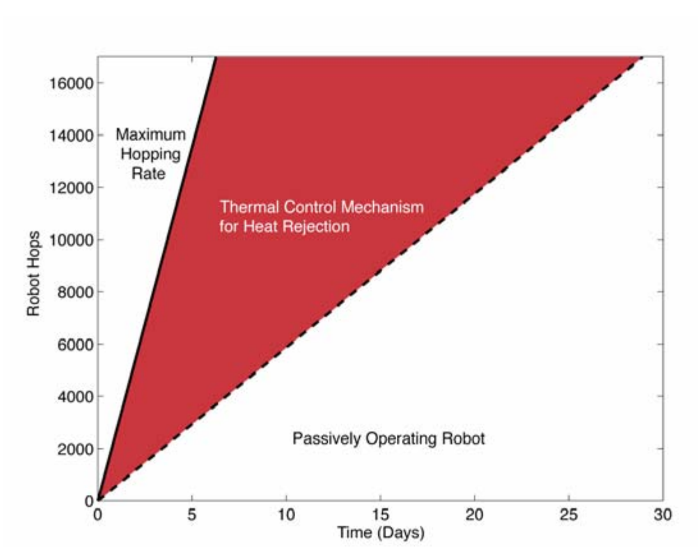

FIGURE 3. Hopping Rates Mission Profile for $\dot{Q}_{loss,av}$ = 0.2 W.

In this case, a thermal control provision must be continuously present in the system to reject excess heat and avoid overheating. Slower hopping rates can also be envisioned; these require modulation of the thermal control. This case is represented by the shaded area in the graph. Decreased hopping rates enable a longer mission duration, as the generated power is used for internal heating purposes and not entirely rejected.

If passive cooling of the robots is considered, without making use of a thermal control mechanism, the fastest hopping rate to avoid overheating is much slower. Below the dotted line, no thermal control mechanism is necessary to compensate for heat released by hopping of the robots.

From Figure 3, it is seen that a heat rejection system has a large influence on the robot mission profile. It facilitates a very time flexible robot deployment. However, as the majority of the proposed concepts and components must still be developed to meet specifications, in essence a curved variable emittance coating surface and a small lightweight, and, ideally, MEMS-embedded heat switch, a thorough analysis by mission planners must be conducted to evaluate the need of a thermal control mechanism for heat rejection, given its influence on the complexity, weight, energy requirements, and cost of the system. Similar mission results are obtained if the robots are passively operated and do not rely on a thermal control provision. A silver coated shell with a silica aerogel insulation layer would prevent the robots from freezing, and, by adjusting the locomotion speed, overheating is avoided. Only mission deployment flexibility would be compromised, as mobility speeds are restricted under passive operation.

CONCLUSIONS

In the present study, the feasibility of a proposed thermal control architecture for planetary and lunar exploration robots is demonstrated. The concept relies a low conductive insulation layer with an actively modulated heat sink to expel waste heat. This approach appears to enable a single, unique design to be employed for all envisioned mission destinations, as the projected heat loss never surpasses the internal heat generation. The universal architecture would allow the robots to be deployed in a very flexible manner and thus reduces development costs.

The Moon is looked at as a first possible mission site for the micro-robots. The proposed mission concept would allow several advantages compared to a traditional rover mission, mainly due to less restricted mobility restraints, especially in caves and heavily cratered terrain. Such a mission would set the stage for later missions, for example on Mars or Jupiter's Galilean moons.

NOMENCLATURE

ΔT_b = body temperature increase after 1 hour of heating (K)
ε_s = shell surface emissivity
$\varepsilon_{s,vec}$ = apparent VEC surface emissivity
λ_{in} = thermal conductivity of insulation (W/m·K)
η_{fc} = fuel cell electrical efficiency
η_{tot} = system thermal efficiency
ρ = density (kg/m^3)
$(\rho \cdot c_p)_b$ = body density – specific heat product (J/m^3·K)
c_p = specific heat (J/kg·K)
A_{cont} = contact area with surface (cm^2)
A_{vec}/A_s = VEC area on shell
D = robot diameter (cm)
D_b = body diameter (cm)
E_{jump} = fuel energy required for one hop (J)
m = robot mass (g)
$\dot{Q}_{cond,g}$ = conductive heat loss to ground (W)
$\dot{Q}_{cond,s}$ = conductive heat loss through insulation layer to shell (W)
$\dot{Q}_{cond,sw}$ = conductive heat loss through heat switch (W)
$\dot{Q}_{conv}$ = convective heat loss (W)
$\dot{Q}_{fc}$ = fuel cell energy production (W)
$\dot{Q}_{heat,fc}$ = fuel cell heat production (W)

$\dot{Q}_{loss}$ = overall robot heat loss to surroundings (W)
$\dot{Q}_{loss,av}$ = average overall robot heat loss (W)
$\dot{Q}_{rad}$ = radiative heat loss (W)
$\dot{Q}_{rad,vec}$ = radiative heat loss with VEC (W)
$\dot{Q}_{sun}$ = absorbed solar irradiation (W)
R_{sw} = heat switch thermal resistance (K/W)
T_{∞} = surrounding temperature (K)
T_b = body temperature (K)
T_s = shell surface temperature (K)
x = insulation layer thickness (mm)

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