Origami Tessellations as Variable Radiative Heat Transfer Devices

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• 3rd Year PhD Student in Mechanical Engineering at Brigham Young University in Provo, Utah
• Funded by the NASA Space Technology Research Fellowship
• Spacecraft experience varying thermal environments
• Radiators are sized to reject the maximum heat load, resulting in non-ideal radiator heat loss for a portion of the spacecraft’s lifetime
A radiator capable of varying its thermal radiative properties would reject the ideal amount of heat to the environment at all times.

- **High Emissivity**: Reject as much heat as possible
- **Low Emissivity**: Hold in as much heat as possible
Variable Radiative Surfaces - Application

- Variable Emissivity Devices would save weight and power
  - 5-7% of spacecraft power is heater related\(^1\)
  - 2-10% of spacecraft dry weight is thermal control\(^1\)
  - Expected power savings from variable emissivity: 90 - 75%\(^1\)

- Variable Emissivity Devices would be especially useful for smaller spacecraft, such as CubeSats
  - Smaller thermal mass means larger temperature swings
  - Less power available for heaters
  - Higher watt density due to compact electronics

How do we modify radiative heat transfer in real time?

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The Cavity Effect - Definition

- Reflections inside a cavity result in increased apparent absorptivity
- Apparent properties depend on cavity geometry

\[ \alpha_a = \frac{G_{\text{absorbed}}}{G_{\text{incident}}} \]
A cavity concentrates emission from all internal surfaces to the cavity opening, increasing the apparent emission from the opening.

\[ \varepsilon_a = \frac{E_{cavity}}{E_{blackbody}} \]
• Different surfaces give different performance
• Deep cavities result in near black behavior
• Cavity emission is **highly directional**, allowing for control of directional radiative heat transfer

**How do we modify radiative heat transfer in real time?**
• Origami tessellations control cavity aspect ratio through actuation
• But what are the apparent radiative properties?
• How would these be applied to a real scenario?
Research Objectives

1. Demonstrate a change in apparent properties with geometry
2. Characterize the apparent emissivity and apparent absorptivity of four tessellations
3. Validate the ability of a dynamically-actuated tessellation to control temperature when exposed to a varying thermal environment.
4. Develop initial radiator prototypes
Demonstrate a change in apparent properties with geometry

OBJECTIVE 1
Objective 1 - Approach

A piece of aluminum shim stock folded into an accordion tessellation was repeatedly heated and cooled in ambient conditions.

The cooling temperature curve gave information about heat losses.

The heating energy balance gave an expression for absorptivity.

\[
\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right) \left[ \frac{U(t)}{\rho w C_p} \right] \theta = \sin\left(\frac{\phi}{2}\right) \frac{\alpha_a G_B}{\rho w C_p} \\
\theta = \sin\left(\frac{\phi}{2}\right) \frac{\alpha_a G_B}{\rho w C_p}
\]

\[
\alpha_a = \frac{U_{max} (\theta - \theta_0)}{G_B} \\
1 - e^{-U_{max} t \sin\left(\frac{\phi}{2}\right) \rho w C_p}
\]
Objective 1 – Results

- Inverse model results\(^2\) were compared to Sparrow’s work\(^3\)
- Apparent absorptivity increase is experimentally verified

\[
\alpha_a = 1 - \left(1 - \alpha X' \right) \left(1 - \alpha \right)^{n-1}
\]

where:

\[
X' = \sin \left( \frac{n - \frac{1}{2}}{2} \phi \right)
\]

\[
n = \left\lfloor \frac{180}{\phi} + \frac{1}{2} \right\rfloor
\]

\[\text{Sparrow’s Equations}\]

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Characterize the apparent radiative properties of four origami tessellations

OBJECTIVE 2
Objective 2 - Definition

- Models must be developed to characterize the apparent radiative properties of origami tessellations

Benefits
- Easy to fold, similar to infinite V-groove.
- Collapses and expands, allowing for storage
- Easy to model and test
Objective 2 - Definition

- Benefits
  - Maintains a constant projected surface area while actuating
  - Two geometry parameters for control
Objective 2 - Definition

Miura-Ori

- Benefits
  - Linear actuation results in 3D movement
  - Three geometry parameters for control
  - Collapses and expands, allowing for storage
Barreto’s Mars

**Benefits**

- Cavities collapse to one side, giving a large absorptivity in one direction and great reflectivity in the other direction
- Collapses to a finite area
- Would give interesting directional behavior
Objective 2 – Approach: Ray Tracing

- Rays are emitted from a surface or irradiated onto a surface.
- This approximates an isothermal surface (for emission).
- The number of rays emitted ($N_{\text{emit}}$) and the number of rays absorbed by the cavity ($N_{\text{absorbed}}$) are counted.

**Apparent Emissivity**

$$\varepsilon_a = \varepsilon \left( \frac{A_{\text{emit}}}{A_{\text{open}}} \right) \left( \frac{N_{\text{escape}}}{N_{\text{emit}}} \right)$$

**Apparent Absorptivity**

$$\alpha_a = \frac{N_{\text{absorb}}}{N_{\text{emit}}} = \varepsilon_a$$

- Diffuse emission
- Diffuse irradiation
Objective 2 – Results: Ray Tracing

Infinite V-groove – Diffuse Irradiation

\[
\varepsilon_a = \varepsilon \Lambda_1 (\varepsilon, \phi) \sum_{n=0}^{\infty} (1-\varepsilon)^n \left[ 1-\sin \left( \frac{\phi}{2} \right) \right]^n = \alpha_a
\]

\[
\Lambda_1 (\varepsilon, \phi) = 1 - \left( 0.0169 - 0.1900 \ln (\varepsilon) \right) \exp \left( -1.4892 \varepsilon^{-0.4040} \phi \right)
\]
Objective 2 – Results: Ray Tracing

Infinite V-groove

Collimated Irradiation – Steep Inclination

Diffuse Irradiation

- Accordion fold results will be similar to infinite V-groove but will depend on the length of the panels as well.
Objective 2 – Results: Ray Tracing

Miura-Ori

Modified V-groove

\[ \varepsilon_a \] vs. \( \phi \) (Degrees)

\[ \varepsilon_a \] vs. \( x/x_0 \)

Infinite V-Groove

- \( \beta = 15 \)
- \( \beta = 45 \)
- \( \beta = 75 \)

Symbols:
- D/W = 3
- D/W = 1
- D/W = 1/3
Validate the ability of a dynamically-actuated tessellation to control temperature when exposed to a varying thermal environment.

OBJECTIVE 3
This work will explore the use of origami tessellations as variable emissivity radiators for spacecraft applications.

To this end, two experiments will be conducted:

- Quantify the net rate of radiative heat exchange with the surroundings.
- Validate the ability of the surface to maintain a given thermal condition in a changing thermal environment.

\[
q_{\text{net\_rad}} = \varepsilon_a A_{\text{projected}} \sigma T^4
\]
Objective 3 – Approach: Net Rad HT

- Consider a flat or folded tessellation subjected to uniform heat generation inside of a vacuum environment.

\[ q_{\text{net, rad}} = \left[ N_{\text{panels}} - 1 \right] \left[ 2W_P \sin\left( \frac{\phi}{2} \right) \right] \delta \varepsilon_{a}(\phi) \left( T_S^4 - T_{\text{surr}}^4 \right) \]

\[ -\alpha_a \cos(\gamma) \left[ \frac{N_{\text{panels}}}{2} \right] 2W_P \sin\left( \frac{\phi}{2} \right) G \]
Objective 3 – Approach: Net Rad HT

- Experimental methods are used to validate the model.
- A sample is heated internally in a vacuum chamber evacuated to below $10^{-5}$ Torr. A thermal camera records apparent temperature data through the sapphire window.
Objective 3 – Results: Net Rad HT

- Diffuse reflection: net radiative heat transfer decreases as the tessellation collapses despite increasing radiative properties
- Specular reflection and collimated irradiation: large changes in radiative properties over small periods are possible

\[
\Pi = \frac{q_\phi}{q_{\phi=180^\circ}}
\]
Objective 3 – Results: Net Rad HT

- Flat and folded experimental results both fall within the bounds established by experimental error
A motorized accordion fold is exposed to varying levels of environmental radiation.

The fold is actuated to the proper cavity angle to maintain steady state conditions.

Objective 3 – Approach: Environment

- Thermal Camera
- Thermocouple
- Motorized Sample
- Heater
- Vacuum Chamber
- Motor
Develop Initial Radiator Prototypes

OBJECTIVE 4
Objective 4 – Final Design Considerations

How do you get the waste heat to the radiator?
How will heat conduct along/between panels?
How will the tessellations be actuated?
Objective 4 - Radiator Concept #1

- Radiator could be built into an existing panel
- The modified V-groove maintains a constant surface area
- Heat pipes bring the heat load from the spacecraft or heat is present on the back of the panel

Main Problem: What do we fill the gap with?
Objective 4 - Radiator Concept #2

Benefits:
1) Low weight due to the compliant hinge

Challenges:
1) Requires constraint
2) Requires conductive, compliant material

- Hinge Assembly (Below)
- Composite Panel (Below)
- Shape Memory Alloy
- VERY conductive filler (heat pipes, carbon sheets, etc.)
- Compliant Conducting Material
- Thin, coated aluminum sheet (for rigidity)
- Bias Spring (if needed. Compliant material should be spring)
- Rivet the composite panel together and secure with thermal epoxy
• What is the fin efficiency?
• Consider panel width, length, thickness, etc.
Objective 4 - Radiator Concept #3

Cold Case

Hot Case
FUTURE WORK
• Moderately shallow cavities exhibit highly directional behavior, largely ignoring emission and absorption at glancing angles.
• This could be utilized to ignore unwanted inputs (solar, albedo, instrument heat loss, etc.)
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- Publications

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APPENDIX
Objective 1 – Approach

- \( U(t) \) characterizes conductive, convective and radiative heat losses

\[
U(t) = q_{\text{convection}} + q_{\text{conduction}} + q_{\text{radiation}} = 2h + 2h_r + \frac{Sk}{A_B}
\]

\[
\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_p}\right] \theta = \sin\left(\frac{\phi}{2}\right) \frac{\alpha_a G_B}{\rho w C_p}
\]
Objective 1 – Approach

- Volume ratio accounts for increasing mass in control volume as sample is actuated

- Different origami folds would have different ratios

\[
\frac{V_B}{V_{folded}} = \frac{A_B}{A_{folded}} = \frac{1}{\sin\left(\frac{\phi}{2}\right)}
\]
At steady state, the energy balance gives absorptivity as a function of $G$, $\theta_{SS}$ and $U_{\text{max}}$

$$\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[ \frac{U(t)}{\rho w C_p} \right] \theta = \sin\left(\frac{\phi}{2}\right) \frac{\alpha_a G_B}{\rho w C_p}$$

All solutions require experimental temperature measurements
Objective 1 – Definition / Approach

- Validate the use of origami tessellations as variable emissivity surfaces
- Experimentally determine the apparent absorptivity of an accordion fold as a function of angle

$$mC_p \frac{dT}{dt} = \alpha_d G_B A_B - (q_{conv} + q_{rad} + q_{cond})_{losses}$$

$$\frac{d\theta}{dt} + \sin \left(\frac{\phi}{2}\right) \left[ \frac{U(t)}{\rho w C_p} \right] \theta = \sin \left(\frac{\phi}{2}\right) \frac{\alpha_d G_B}{\rho w C_p}$$

Heat Loss Term  Heat Addition Term
# Objective 1 - Approach

\[
\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_p}\right] \theta = \sin\left(\frac{\phi}{2}\right) \frac{\alpha_a G_B}{\rho w C_p}
\]

## Integrating Factor Method

\[\alpha_a = \frac{U_{\text{max}}}{G_B} \left(\theta - \theta_0\right) - \frac{U_{\text{max}}}{G_B} \sin\left(\frac{\phi}{2}\right) \left[1 - e^{\rho w C_p} \sin\left(\frac{\phi}{2}\right)\right]
\]

## Direct Method

\[\alpha_a = \frac{\rho w C_p}{G_B} \sin\left(\frac{\phi}{2}\right) \left[\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right) \frac{U(\Delta T(t))}{\rho w C_p} \theta\right]
\]

## Diagram

- **Air Piston**
- **Insulated Shutter**
- **Blackbody Radiator**
- **Thermocouples**
- **IR Camera**
- **Folded Sample**
- **Insulation Shield**
Objective 1 – Results

- Flat sample was measured with a reflectometer
- Independent verification of inverse model results

<table>
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<th>Test #</th>
<th>Spectral Range (Micrometers)</th>
<th>Spectral Reflectivity</th>
<th>Emissometer Absorptivity</th>
<th>Steady State Model Absorptivity</th>
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<td>0.969</td>
<td>0.973</td>
<td>0.977</td>
</tr>
</tbody>
</table>

\[ \alpha = \sum_{i=1}^{6} F_i \left(1 - \rho_{r,i}\right) \]
Objective 1 – Approach

T = 1000 °C

Air Piston

Blackbody Radiator

Insulation Shield

15.25 cm

Thermocouples

Insulated Shutter

Folded Sample

T = 1000 °C

Objective 1 – Approach

\[ U(t) \]
Objective 1 – Results

- Apparent absorptivity results with respect to time for the three methods
- All solutions converge to one value
Ray Tracing – Emissivity Thermal Model

From the definition of $Q_{\text{emit}}$

$$\sigma T^4 = \frac{Q_{\text{emit}}}{\varepsilon A_{\text{emit}}}$$

Plug into apparent emissivity equation

$$\varepsilon_a = \varepsilon \frac{A_{\text{emit}}}{A_{\text{opening}}} \left[1 - \frac{Q_{\text{absorb}}}{Q_{\text{emit}}} \right]$$

Using the original energy balance and equating thermal model to ray tracing results gives:

$$\varepsilon_a = \varepsilon \frac{A_{\text{emit}}}{A_{\text{opening}}} \frac{Q_{\text{escape}}}{Q_{\text{emit}}} = \varepsilon \frac{A_{\text{emit}}}{A_{\text{opening}}} \frac{N_{\text{escape}}}{N_{\text{emit}}}$$

Rearrange to give apparent emissivity

$$\varepsilon_a = \varepsilon \frac{A_{\text{emit}}}{A_{\text{opening}}} - \frac{Q_{\text{absorb}}}{\sigma T^4 A_{\text{opening}}}$$
From definition of apparent reflectivity

\[ Q_{\text{escape}} = \rho_a Q_{\text{emit}} \]

\[ Q_{\text{emit}} - \rho_a Q_{\text{emit}} = Q_{\text{absorb}} \]

\[ Q_{\text{emit}} = Q_{\text{absorb}} + Q_{\text{escape}} \]

Assuming opaque

\[ 1 - \rho_a = \alpha_a \]

Final Expression

\[ \alpha_a = \frac{Q_{\text{absorb}}}{Q_{\text{emit}}} = \frac{N_{\text{absorb}}}{N_{\text{emit}}} \]

From Ohwada\[1\] we learn that apparent absorptivity and apparent emissivity are equivalent for an isothermal cavity.

\[ \alpha_a = \frac{N_{\text{absorb}}}{N_{\text{emit}}} = \varepsilon_a \]

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Apparent emissivities below the intrinsic surface value are a result of the area of the sides.

Values above unity are not possible and are due to large error experienced at very small angles and high emissivities.

\[ \varepsilon_a = \varepsilon \frac{A_{emit}}{A_{opening}} \frac{N_{escape}}{N_{emit}} \]
All cases showed a convergence of 0.2% or less. The extreme cases are shown here (L/S = 1 or 5 and emissivity = 0.028 or 0.9)