A Modelica Library for Spacecraft Thermal Analysis

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DLR

Outline

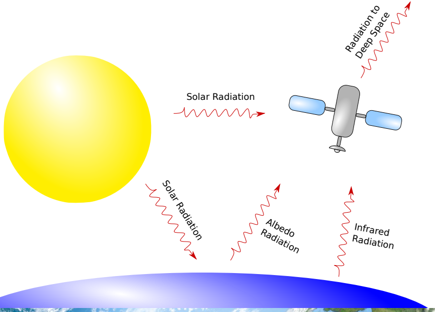
Goal

Motivation

- High temperature differences of spacecrafts over the course of an orbit
- Each component has specific temperature limits

Thermal Dynamics

$$C\dot{T} = Q^{\mathrm{alb}} + Q^{\mathrm{sun}} + Q^{\mathrm{planet}} - Q^{\mathrm{ds}} + Q^{r}$$



Radiations

Direct Solar Radiation

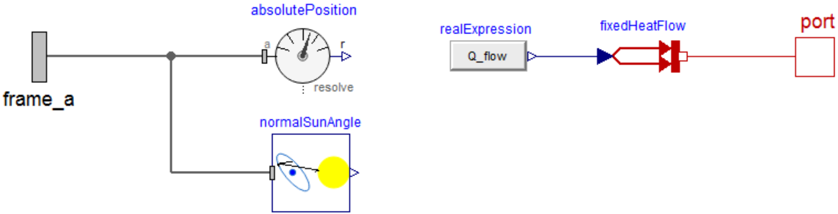
Solar constant varying over distance

$$G_s(d) = G_{s0}\left(\frac{d_0}{d}\right)^2 .$$

Solar Irradiation is calculated as

$$Q^{\mathrm{sun}} = \begin{cases} \alpha G_s\left(\frac{\|s-r\|}{1\,\mathrm{au}}\right) A\cos(\phi)\nu & \text{if } 0 < \phi < \frac{\pi}{2} \\ 0 & \text{if } \frac{\pi}{2} < \phi < \pi \end{cases} .$$

- α solar absorptance of the surface
- A area of the surface
- $\phi = \angle(n, s)$ angle between surface and sun
- ν Shadow factor



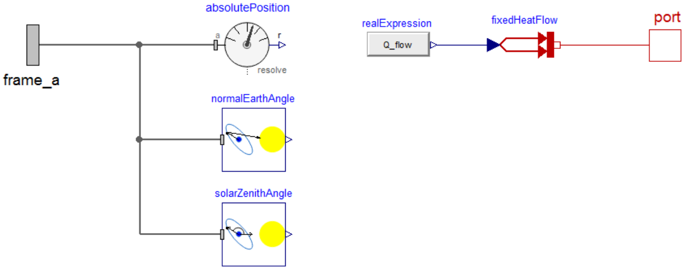
Radiations

Albedo Radiation

Albedo radiation is calculated as

$$Q^{\mathrm{alb}} = \begin{cases} \rho_{\mathrm{alb}} \alpha G_s\left(\left(\frac{\|s-r\|}{1\,\mathrm{au}}\right)\right) A F_{\mathrm{form}}(r,n)\cos(\xi) & \text{if } 0 < \xi < \frac{\pi}{2} \\ 0 & \text{if } \frac{\pi}{2} < \xi < \pi \end{cases}$$

- ρ_{alb} albedo coefficient
- F_{form} Form factor
- r distance to spacecraft
- n normal of surface
- $\xi = \angle(r,s)$ solar zenith angle



Radiations

Planetary Radiation

Planetary Radiation is calculated as

$$Q^{\text{planet}} = \varepsilon A F_{\text{form}}(r, n) I_{\text{IR}}$$

with

- ε infra-red emissivity of the surface
- I_{IR} intensity of earth infra-red flux

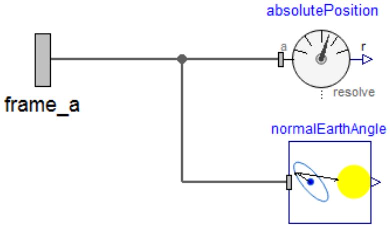
Radiation to Deep Space

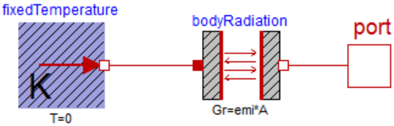
Radiation to deep space is calculated as

$$Q^{\text{ds}} = \varepsilon A \sigma T^4$$

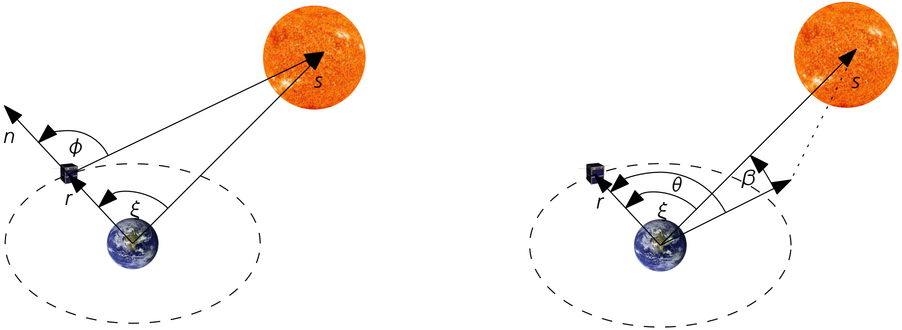
with

- T temperature of the spacecraft





Thermal Angles



Solar Angles

- ϕ between surface normal n and sun $s \rightsquigarrow Q^{\mathrm{sun}}$
- ξ solar zenith angle between spacecraft r and sun $s \rightsquigarrow Q^{\mathrm{alb}}$
- $F_{\mathrm{form}}(r, n)$ Form factor described by spacecraft r and sun $s \rightsquigarrow Q^{\mathrm{alb}}, Q^{\mathrm{planet}}$
- θ between spacecraft r and the solar noon
- β between orbit plane and sun s

Angle Calculation

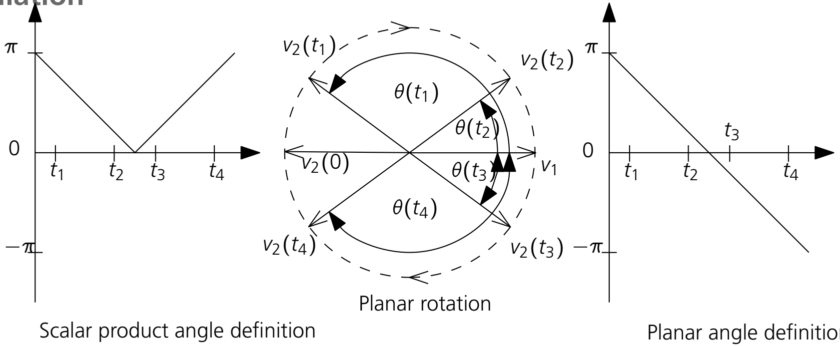


Figure: Angle of a planar rotation described by two different definitions

Scalar Product Angle

$$\theta := \cos^{-1}\left(\frac{v_1^\top v_2}{\|v_1\|\|v_2\|}\right)$$

Planar Angle

$$\theta := \operatorname{atan2}(e_2 T v_2, e_1 T v_2) - \operatorname{atan2}(e_2 T v_1, e_1 T v_1)\ .$$

Coordinate System Calculation

Aim

Construct of two vectors v_1, v_2 a coordinate system (x, y, z) which is constant over time and v_1 and v_2 are in the x, y plane

Cross Product Definition

$$x = \frac{v_1}{\|v_1\|},$$

$$y = z \times x,$$

$$z = \frac{v_1 \times v_2}{\|v_1 \times v_2\|}.$$

Gram Schmidt

$$x = \frac{v_1}{\|v_1\|},$$

$$y = \frac{v_2 - (x^\top v_2)x}{\|v_2 - (x^\top v_2)x\|},$$

$$z = \frac{v_3 - (x^\top v_3)x - (y^\top v_3)y}{\|v_3 - (x^\top v_3)x - (y^\top v_3)y\|}.$$

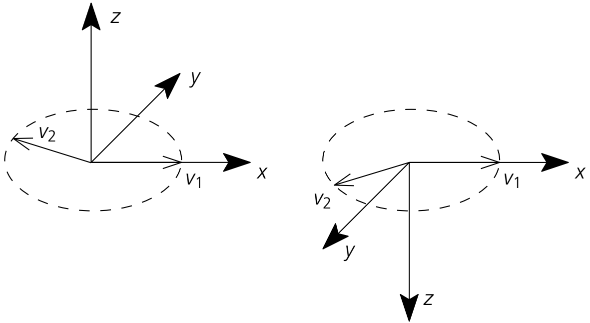
Coordinate System Calculation

Cross Product Definition

$$x = \frac{v_1}{\|v_1\|} \,,$$

$$y = z \times x \,,$$

$$z = \frac{v_1 \times v_2}{\|v_1 \times v_2\|} \,.$$



Coordinate System Calculation

Gram Schmidt Definition

$$x = \frac{v_1}{\|v_1\|},$$

$$y = \frac{v_2 - (x^\top v_2)x}{\|v_2 - (x^\top v_2)x\|},$$

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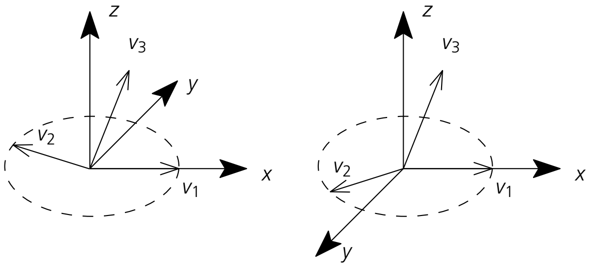

Coordinate System Calculation

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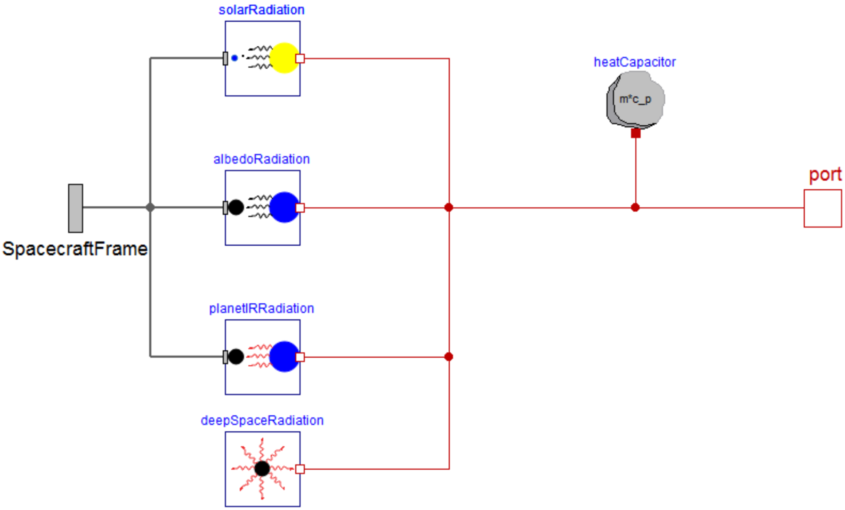
Suggested Approach

$$x = x^{\mathrm{Gram}} ,$$
$$y = z \times x ,$$
$$z = z^{\mathrm{Gram}} .$$

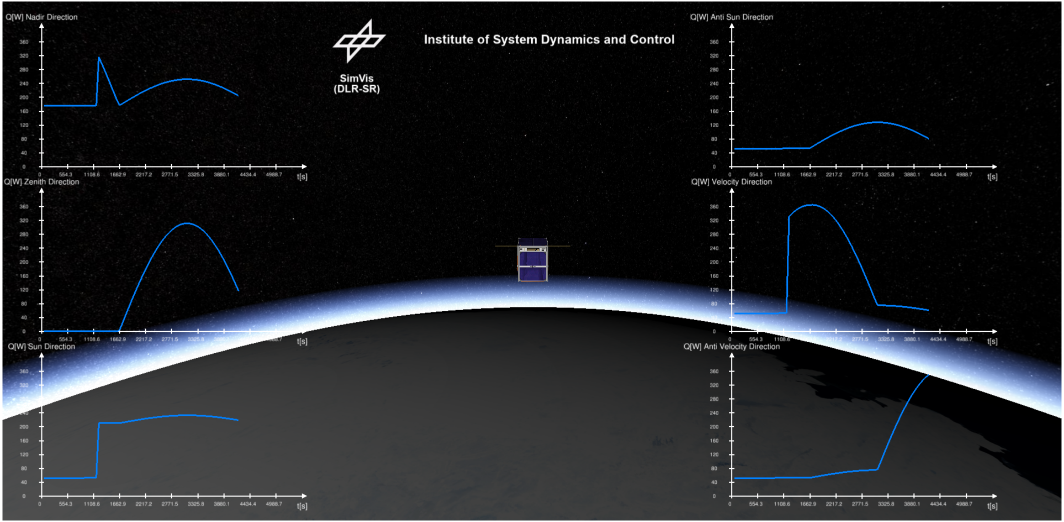
Properties

- Additional vector v_3 is necessary to allow unique definition
- v_3 must always be not parallel to v_1-v_2 plane

Implementation



Simulation


Q[W] Nadir Direction
Q[W] Zenith Direction
Q[W] Sun Direction
Q[W] Anti Sun Direction
Q[W] Velocity Direction
Q[W] Anti Velocity Direction
t[s]
SimVis
(DLR-SR)
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Conclusions

The proposed library includes

- thermal angle calculations
- environmental heat fluxes
- thermal dynamics

Future work

- will incorporate the presented library into the design of an energy management

Shadow Function

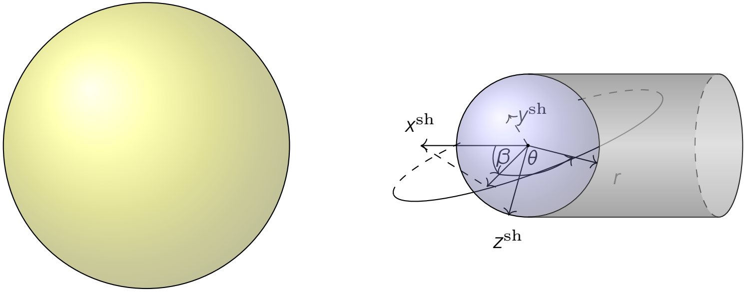

Figure: Cylindrical Shadow Model

Calculation of the shadow coefficient

The shadow coefficient is calculated as

$$\nu = \begin{cases} 1 & \text{if } |\theta| > \frac{\pi}{2} \land \sqrt{\cos(\theta)^2 \sin(\beta)^2 + \sin(\theta)^2} < \frac{r_\oplus}{\|r\|} \\ 0 & \text{otherwise} \end{cases} . \tag{1}$$

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Thermal Dynamics

$$C\dot{T} = Q^{\mathrm{alb}} + Q^{\mathrm{sun}} + Q^{\mathrm{planet}} - \varepsilon A \sigma T^4 + Q^r$$

Radiations

- Direct Solar irradiation Q^{sun}
- Albedo radiation Q^{alb}
- Planetary Radiation Q^{planet}
- Radiation to Deep Space
- Dissipative energy Q^r