Autonomous Vehicle Simulation (AVS) Laboratory, University of Colorado

Basilisk Technical Memorandum

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SUN POINTING USING A BODY-RELATIVE SUN DIRECTION VECTOR AND RATE GYRO INFORMATION

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Status: Released

Scope/Contents

This module provides the attitude guidance output for a sun pointing mode. This could be used for safe mode, or a power generation mode. The input is the sun direction vector which doesn't have to be normalized, as well as the body rate information. The output is the standard BSK attitude reference state message. The sun direction measurement is cross with the desired body axis that is to point at the sun to create a principle rotation vector. The dot product between these two vectors is used to extract the principal rotation angle. With these a tracking error MRP state is computer. The body rate tracking errors relative to the reference frame are set equal to the measured body rates to bring the vehicle to rest when pointing at the sun. Thus, the reference angular rate and acceleration vectors relative to the inertial frame are nominally set to zero. If the sun vector is not available, then the reference rate is set to a body-fixed value while the attitude tracking error is set to zero. Further, robustness cases

Rev	Change Description	By	Date
1.0	First Documentation of this module, even though the module was one of the first BSK modules drafted.	H. Schaub	2018-04-28
1.1	Can now handle the case where the sun direction vector is not available	H. Schaub	2018-04-28
1.2	Can now handle the case where the sun heading and commanded bod vectors are collinear	H. Schaub	2018-04-28
1.3	Corrected module input and output message to comply with BSK naming conventions	H. Schaub	2018-04-29

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1 Model Description

1.1 Module Goal

This attitude guidance module has the goal of aligning a commanded body-fixed spacecraft vector $\hat{\boldsymbol{s}}_c$ with another input vector $\boldsymbol{s}$. If $\hat{\boldsymbol{s}}_c$ is for example the solar panel normal vector, and $\boldsymbol{s}$ is the current sun heading vector, this module will compute the attitude tracking errors to align the solar panels towards the sun, i.e. achieve sun pointing. Sun pointing is a mode for general recharging the spacecraft, but is also a common guidance scenario with Safe Mode.

Besides $\boldsymbol{s}$, the second input vector is the inertial body angular velocity vector $\boldsymbol{\omega}_{B/N}$. The sun pointing frame is assumed to be at rest, thus the attitude rate tracking error is set either equal to the body rates to bring the body to rest, or difference with a specified rotation about the sun heading vector to achieve a final roll about this heading vector.

As the desired sun pointing orientation is inertial, the inertial reference frame acceleration $\dot{\boldsymbol{\omega}}_{R/N}$ is set to zero, while the reference rate is either zero or the desired sun-heading roll vector.

Note that this module does not establish a unique sun-pointing reference frame. Rather, the pointing condition, align $\hat{\boldsymbol{s}}_c$ with $\boldsymbol{s}$ is an under-determined 2 degree of freedom condition. Thus, the rotation angle about $\boldsymbol{s}$ is left to be arbitrary in this sun pointing module. For the sun pointing applications this is a very practical result as the power generation does not depend on the orientation about $\boldsymbol{s}$.

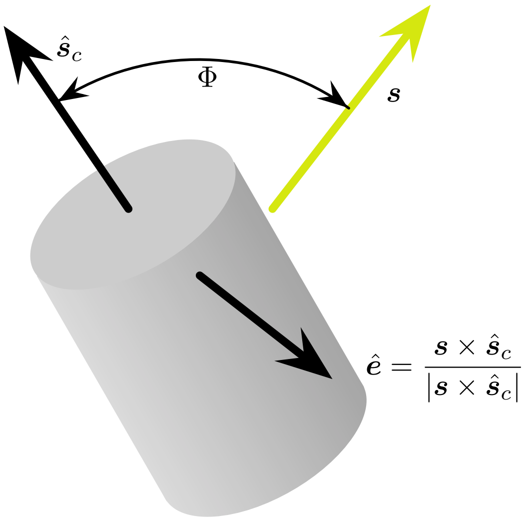

Fig. 1: Body Vector Illustrations.

1.2 Equations

1.2.1 Good Sun Direction Vector Case

In the following mathematical developments all vectors are assumed to be taken with respect to a body-fixed frame $\mathcal{B}$. The attitude of the body $\mathcal{B}$ relative to the reference frame $\mathcal{R}$ is written as a principal rotation from $\mathcal{R}$ to $\mathcal{B}$. Thus, the associated principal rotation vector $\hat{\boldsymbol{e}}$ is

$$\hat{\boldsymbol{e}} = \frac{\boldsymbol{s} \times \hat{\boldsymbol{s}}_c}{|\boldsymbol{s} \times \hat{\boldsymbol{s}}_c|} \tag{1}$$

Note that the sun direction vector $\boldsymbol{s}$ does not have to be a normalized input vector.

The principal rotation angle between the two vectors is given through

$$\Phi = \arccos\left(\frac{\boldsymbol{s} \cdot \hat{\boldsymbol{s}}_c}{|\boldsymbol{s}|}\right) \tag{2}$$

Next, this rotation from $\mathcal{R}$ to $\mathcal{B}$ is written as a set of MRPs through

$$\boldsymbol{\sigma}_{B/R} = \tan\left(\frac{\Phi}{4}\right)\hat{\boldsymbol{e}} \tag{3}$$

The set $\boldsymbol{\sigma}_{B/R}$ is the attitude error of the output attitude guidance message.

The module allows for a nominal spin rate about the sun heading axis by specifying the module parameter `sunAxisSpinRate` called $\dot{\theta}$ in this description. The nominal spin rate is thus given by

$${}^{\mathcal{B}}\boldsymbol{\omega}_{R/N} = {}^{\mathcal{B}}\hat{\boldsymbol{s}}\dot{\theta} \tag{4}$$

Note that this constant nominal spin is only for the case where the sun is visible and the sun-heading vector measurement is available.

If the spacecraft is to be brought to rest $\boldsymbol{\omega}_{R/N} = \boldsymbol{0}$, then $\dot{\theta}$ should be set to zero. The tracking error angular velocity vector is computed using.

$$\boldsymbol{\omega}_{B/R} = \boldsymbol{\omega}_{B/N} - \boldsymbol{\omega}_{R/N} \tag{5}$$

Finally, the attitude guidance message must specify the inertial reference frame acceleration vector. This is set to zero as the roll about the sun heading is assumed to have a constant magnitude and inertial heading.

$$\dot{\boldsymbol{\omega}}_{R/N} = \boldsymbol{0} \tag{6}$$

1.2.2 No Sun Direction Vector Case

If Φ is less then then module parameter `minUnitMag`, then it is assumed that no good sun heading vector is available and the attitude tracking error $\boldsymbol{\sigma}_{B/R}$ is set to zero.

Further, if the sun is not visible, the module allows for a non-zero body rate to be prescribed. This allows the spacecraft to engage in a constant rate tumble specified through the module configuration vector `omega_RN_B`. In this case the tracking error rate is evaluate through

$$\boldsymbol{\omega}_{B/R} = \boldsymbol{\omega}_{B/N} - \boldsymbol{\omega}_{R/N} \tag{7}$$

and the output message reference rate is set equal to the prescribed $\boldsymbol{\omega}_{R/N}$ while the reference acceleration vector $\dot{\boldsymbol{\omega}}_{R/N}$ is set to zero.

1.2.3 Collinear Commanded and Sun Heading Vectors

First consider the case where $\boldsymbol{s} \approx \hat{\boldsymbol{s}}_c$. In this case the cross product in Eq. (1) is not well defined. Let ϵ be a pre-determined small angle. Then, if $\Phi < \epsilon$ the attitude tracking error is set to

$$\boldsymbol{\sigma}_{B/R} = \boldsymbol{0}$$

However, if $\boldsymbol{s} \approx -\hat{\boldsymbol{s}}_c$, then an eigen-axis $\hat{\boldsymbol{e}}$ that is orthogonal to $\hat{\boldsymbol{s}}_c$ must be determined. Let the body frame be defined through $\mathcal{B} : \{\hat{\boldsymbol{b}}_1, \hat{\boldsymbol{b}}_2, \hat{\boldsymbol{b}}_3\}$. The eigen-axis is determined first by taking a cross product with $\hat{\boldsymbol{b}}_1$:

$$\hat{\boldsymbol{e}}_{180} = \frac{\hat{\boldsymbol{s}}_c \times \hat{\boldsymbol{b}}_1}{|\hat{\boldsymbol{s}}_c \times \hat{\boldsymbol{b}}_1|} \tag{8}$$

If $\hat{\boldsymbol{s}}_c \approx \hat{\boldsymbol{b}}_1$, then this $\hat{\boldsymbol{e}}$ vector will have a small norm. In this ill-determined case, the $\hat{\boldsymbol{e}}$ vector is determined using

$$\hat{\boldsymbol{e}}_{180} = \frac{\hat{\boldsymbol{s}}_c \times \hat{\boldsymbol{b}}_2}{|\hat{\boldsymbol{s}}_c \times \hat{\boldsymbol{b}}_2|} \tag{9}$$

As $\hat{\boldsymbol{s}}_c$ cannot both be aligned with $\hat{\boldsymbol{b}}_1$ and $\hat{\boldsymbol{b}}_2$, this algorithm determines a unique eigen axis $\hat{\boldsymbol{e}}_{180}$ for the case that the principal rotation angle is close to 180 degrees, or $\pi - \Phi < \epsilon$. This special case eigen axis is only computed once in the module reset routine.

In this scenario the angular velocity tracking error is evaluated using the same method as outlined in section 1.2.1.

2 Module Functions

- **Compute the attitude tracking error**: Determines the shortest rotation to align $\boldsymbol{s}$ and $\hat{\boldsymbol{s}}_c$, and computes the corresponding three-dimensional attitude difference

- **Control spacecraft rotation**: The reference frame is assumed to be non-accelerating and either zero (default) or a constant spin about the sun heading axis.

- **Robust to no sun heading information**: If the sun heading vector is not available, then the attitude feedback is turned off by zeroing $\boldsymbol{\sigma}_{B/R}$. Instead of driving the body rates to zero, the body rates are driven to a prescribed $\boldsymbol{\omega}_{R/N}$ vector. This allow the spacecraft to search for the sun and covers the case if some sun sensors are offline.

- **Robust to collinear observation vector**: The module must handle the cases where the commanded body relative vector and the sun direction vectors are nearly collinear.

3 Module Assumptions and Limitations

The module input vector $\boldsymbol{s}$ can be a vector of any length except for a zero-length vector. The commanded body-relative unit direction vector $\boldsymbol{s}_c$ is assumed to be fixed relative to the body.

4 Test Description and Success Criteria

The mathematics in this module are straight forward and can be tested in a series of input and output evaluation tests.

4.1 Check 1

Here a check is performed where the sun vector measurement $\boldsymbol{s}$ has a non-zero length and is not aligned with $\hat{\boldsymbol{s}}_c$.

4.2 Check 2

The sun direction vector $\boldsymbol{s}$ is given a norm value that is less than `minUnitMag`. In this case the attitude tracking $\boldsymbol{\sigma}_{B/R}$ should be set to zero. Further, the body rate errors are now evaluated relative to a fixed $\boldsymbol{\omega}_{R/N}$ vector.

4.3 Check 3

The sun direction vector $\boldsymbol{s}$ aligned with $\hat{\boldsymbol{s}}_c$. In this case the attitude tracking $\boldsymbol{\sigma}_{B/R}$ should be set to zero. Further, the body rate errors are simply the inertial body angular rates.

4.4 Check 4

The sun direction vector $\boldsymbol{s} \approx -\hat{\boldsymbol{s}}_c$. In this case the attitude tracking $\boldsymbol{\sigma}_{B/R}$ should be set to $\hat{e}_{180}$. Further, the body rate errors are simply the inertial body angular rates.

4.5 Check 4

The sun direction vector $\boldsymbol{s} \approx -\hat{\boldsymbol{s}}_c$, but $\hat{\boldsymbol{s}}_c = \hat{\boldsymbol{b}}_1$. In this case the attitude tracking $\boldsymbol{\sigma}_{B/R}$ should be set to $\hat{e}_{180}$ that is evaluated with the cross product with $\hat{\boldsymbol{b}}_2$. Further, the body rate errors are simply the inertial body angular rates.

5 Test Parameters

The unit test verify that the module output guidance message vectors match expected values.

Table 2: Error tolerance for each test.

Output Value Tested	Tolerated Error
$\boldsymbol{\sigma}_{B/R}$	1e-12
$\boldsymbol{\omega}_{B/R}$	1e-12
$\boldsymbol{\omega}_{R/N}$	1e-12
$\dot{\boldsymbol{\omega}}_{R/N}$	1e-12

The nominal module test input values are $\hat{\boldsymbol{s}}_c = (0, 0, 1)$, $\boldsymbol{s} = (1, 0, 0)$ and ${}^{\mathcal{B}}\boldsymbol{\omega}_{B/N} = (0.01, 0.50, -0.20)$ rad/sec. The nominal body-fixed search rate is set to ${}^{\mathcal{B}}\boldsymbol{\omega}_{R/N} = (0.0, 0.0, 0.1)$ rad/sec. This rate is only used if no sun direction vector is available. The small angle is set to $\epsilon = 0.01$ degrees.

6 Test Results

All of the tests passed:

Table 3: Test results

Check	Pass/Fail
1	PASSED
2	PASSED
3	PASSED
4	PASSED
5	PASSED

7 User Guide

7.1 Input/Output Messages

The module has 2 required input messages, and 1 output message:

- `attGuidanceOutMsgName` – This output message, of type `AttGuidFswMsg`, provide the attitude tracking errors and the reference frame states.
- `sunDirectionInMsgName` – This input message, of type `NavAttIntMsg`, receives the sun heading vector $\boldsymbol{s}$
- `imuInMsgName` – This input message, of type `IMUSensorBodyFswMsg`, receives the inertial angular body rates $\boldsymbol{\omega}_{B/N}$

7.2 Module Parameters and States

The module has the following parameter that can be configured:

- `sHatBdyCmd` – [REQUIRED] This 3x1 array contains the commanded body-relative vector $\hat{\boldsymbol{s}}_c$ that is to be aligned with the sun heading $\boldsymbol{s}$
- `minUnitMag` – This double contains the minimum norm value of $\boldsymbol{s}$ such that a tracking error attitude solution $\boldsymbol{\sigma}_{B/R}$ is still computed. If the norm is less than this, then $\boldsymbol{\sigma}_{B/R}$ is set to zero. The default `minUnitMag` value is zero.
- `omega_RN_B` – This vectors specifies the body-fixed search rate to rotate and search for the sun if no good sun direction vector is visible. Default value is a zero vector.
- `smallAngle` – This double specifies what is considered close for $\boldsymbol{s}$ and $\hat{\boldsymbol{s}}_c$ to be collinear. Default value is zero.
- `sunAxisSpinRate` – Specifies the nominal spin rate about the sun heading vector. This is only used if a sun heading solution is available. Default value is zero bring the spacecraft to rest.