Autonomous Vehicle Simulation (AVS) Laboratory, University of Colorado

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POINTING USING A CAMERA-RELATIVE OPNAV DIRECTION AND RATE GYRO INFORMATION

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Scope/Contents

This module provides the attitude guidance output for an opNav pointing mode. Typically this would be to point to a planet center, or a specific heading determined from a camera. The input is an optical navigation direction vector, as well as the body rate information. The output is the standard BSK attitude reference state message. The target direction measurement is crossed with the desired camera 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 computed. The body rate tracking errors, relative to the inertial frame, are set equal to the measured body rates to bring the vehicle to rest when pointing at the target. Thus, the reference angular rate and acceleration vectors relative to the inertial frame are nominally set to zero. If no heading is available, then the reference rate is set to a camera-fixed value while the attitude tracking error is set to zero.

Rev	Change Description	By	Date
1.0	First Documentation of this module: Nearly Identical to sunSafePoint	T. Teil	2019-09-01

Contents

1 Model Description

1.1 Module Goal

This attitude guidance module has the goal of aligning a commanded camera-fixed spacecraft vector $\hat{\boldsymbol{h}}_c$ with another input vector $\boldsymbol{h}$. If $\hat{\boldsymbol{h}}_c$ is the camera boresight, this module will compute the attitude tracking errors to align the camera towards the target, i.e. achieve relative pointing.

Besides $\boldsymbol{h}$, the second input vector is the inertial body angular velocity vector $\boldsymbol{\omega}_{B/N}$. As the desired planet pointing orientation is unknown, the inertial reference frame acceleration $\dot{\boldsymbol{\omega}}_{R/N}$ is set to zero,.

Note that this module does not establish a unique target-pointing reference frame. Rather, it simply aligns $\hat{\boldsymbol{h}}_c$ with $\boldsymbol{h}$ which is an under-determined 2 degree of freedom condition. Thus, the rotation angle about $\boldsymbol{h}$ is left to be arbitrary in this planet pointing module.
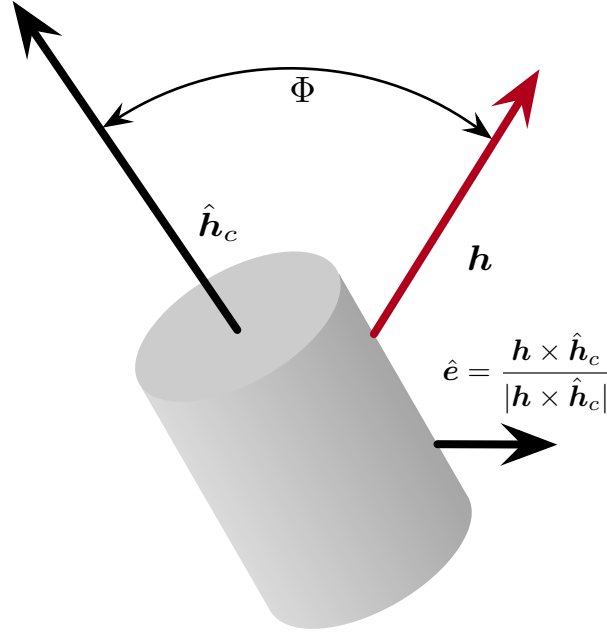
Fig. 1: Body Vector Illustrations.

1.2 Equations

1.2.1 Good Planet Direction Vector Case

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

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

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

The principal rotation angle between the two vectors is given through

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

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

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

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

While the attitude errors are tracked in the camera frame, the rates are tracked in the body frame. This can be done since the camera is fixed in the body frame. The module allows for a nominal spin rate about the planet heading axis by specifying the module parameter `planetAxisSpinRate` called $\dot{\theta}$ in this description. The nominal spin rate is thus given by

$$^{\mathcal{B}}\boldsymbol{\omega}_{R/N} = [\mathcal{BC}]^{\mathcal{C}}\hat{\langle}\dot{\theta} \tag{4}$$

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

If the spacecraft is to be brought to rest, $\boldsymbol{\omega}_{R/N} = \mathbf{0}$, 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 planet heading is assumed to have a constant magnitude and inertial heading.

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

1.2.2   No planet Direction Vector Case

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

Further, if the planet 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 evaluated 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 Planet Heading Vectors

First consider the case where $\boldsymbol{h} \approx \hat{\boldsymbol{h}}_c$. 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 $\boldsymbol{\sigma}_{C/R} = \mathbf{0}$.

However, if $\boldsymbol{h} \approx -\hat{\boldsymbol{h}}_c$, then an eigen-axis $\hat{\boldsymbol{e}}$ that is orthogonal to $\hat{\boldsymbol{h}}_c$ 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 $\hat{\boldsymbol{b}}_1$:

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

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

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

As $\hat{\boldsymbol{h}}_c$ cannot be aligned with both $\hat{\boldsymbol{b}}_1$ 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 $\boldsymbol{h}$ and $\hat{\boldsymbol{h}}_c$, 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 planet heading axis.

- **Robust to no planet heading information**: If the planet heading vector is not available, then the attitude feedback is turned off by zeroing $\boldsymbol{\sigma}_{C/R}$. 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 planet and covers the case if some planet sensors are offline.

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

3 Module Assumptions and Limitations

The module input vector $\boldsymbol{h}$ can be a vector of any length except for a zero-length vector.

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 planet heading vector measurement $\boldsymbol{h}$ has a non-zero length and is not aligned with $\hat{\boldsymbol{h}}_c$.

4.2 Check 2

The planet direction vector $\boldsymbol{h}$ 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 planet direction vector $\boldsymbol{h}$ aligned with $\hat{\boldsymbol{h}}_c$. 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 planet direction vector is not given. The spacecraft is given a search rate as a sole command.

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
$\boldsymbol{\sigma}_{C/R}$	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 $\hat{\boldsymbol{h}}_c = (0, 0, 1)$, $\boldsymbol{h} = (1, 0, 0)$ 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 planet 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

7   User Guide

7.1   Input/Output Messages

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

- `attGuidanceOutMsg` − This output message, of type `AttGuidMsgPayload`, provide the attitude tracking errors and the reference frame states.

- `opnavDataInMsg` − This input message, of type `OpNavMsgPayload`, receives the planet heading vector h

- `imuInMsg` − This input message, of type `NavAttMsgPayload`, receives the inertial angular body rates $\omega_{B/N}$

- `cameraConfigInMsg` − This input message, of type `CameraConfigMsgPayload`, receives the camera specs, notably the DCM: $[CB]$

7.2   Module Parameters and States

The module has the following parameter that can be configured:

- `alignAxis_C` − [REQUIRED] This 3x1 array contains the commanded camera-relative vector $\hat{h}_c$ that is to be aligned with the planet heading h

- `minUnitMag` − This double contains the minimum norm value of h such that a tracking error attitude solution $\sigma_{B/R}$ is still computed. If the norm is less than this, then $\sigma_{B/R}$ 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 target vector is visible. Default value is a zero vector.

- `smallAngle` − This double specifies what is considered close for h and $\hat{h}_c$ to be collinear. Default value is zero.

- `opNavAxisSpinRate` − Specifies the nominal spin rate about the planet heading vector. This is only used if a heading solution is available. Default value is zero bring the spacecraft to rest.