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Basilisk Technical Memorandum
Document ID: Basilisk-MagneticField
MAGNETIC FIELD ENVIRONMENT

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Status: Released
Scope/Contents
The MagneticField class is used to calculate the magnetic field vector above a body using multiple models. This class is used to hold relevant planetary magnetic field properties to compute answers for a given set of spacecraft locations relative to a specified planet. Planetary parameters, including position and input message, are settable by the user. In a given simulation, each planet of interest should have only one magnetic field model associated with it linked to the spacecraft in orbit about that body.

Rev	Change Description	By	Date
1.0	Initial release	H. Schaub	03-12-2019

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1 Model Description

The purpose of this module is to implement a magnetic field model that rotates with a planet fixed frame $\mathcal{E} : \{\hat{e}_1, \hat{e}_2, \hat{e}_3\}$. Here \hat{e}_3 is the typical positive rotation axis and \hat{e}_1 and \hat{e}_2 span the planet's equatorial plane.

MagneticField represents a single interface to a variety of magnetic field models within the BSK framework. These are briefly summarized here for reference. By invoking the magnetic field module, the default values are set such that the centered dipole model is simulated about Earth. The reach of the model controlled by setting the variables `envMinReach` and `envMaxReach` to positive values. These values are the radial distance from the planet center. The default values are -1 which turns off this checking where the atmosphere model as unbounded reach.

There are a multitude of magnetic field models.* The goal with Basilisk is to provide a simple and consistent interface to a range of models. The list of models is expected to grow over time.

1.1 Planet Centric Spacecraft Position Vector

For the following developments, the spacecraft location relative to the planet frame is required. Let $\mathbf{r}_{B/P}$ be the spacecraft position vector relative to the planet center. In the simulation the spacecraft location is given relative to an inertial frame origin O . The planet centric position vector is computed using

$$\mathbf{r}_{B/P} = \mathbf{r}_{B/O} - \mathbf{r}_{P/O} \quad (1)$$

If not planet ephemeris message is specified, then the planet position vector $\mathbf{r}_{P/O}$ is set to zero.

* <https://geomag.colorado.edu/geomagnetic-and-electric-field-models.html>

Let $[EN]$ be the direction cosine matrix¹ that relates the rotating Earth-fixed frame relative to an inertial frame $\mathcal{N} : \{\hat{n}_1, \hat{n}_2, \hat{n}_3\}$. The simulation provides the spacecraft position vector in inertial frame components. The planet centric position vector is then written in Earth-fixed frame components using

$${}^{\mathcal{E}}\mathbf{r}_{B/P} = [EN] {}^{\mathcal{N}}\mathbf{r}_{B/P} \quad (2)$$

1.2 Centered Dipole Magnetic Field Model

The centered dipole model is a first order result of the more complex spherical harmonic modeling of the planet's magnetic field.² There are several solution that provide an answer in the local North-Earth-Down or NED frame,³ or in the local spherical coordinates. Let \mathbf{m} be the magnetic dipole vector which is then defined as²

$$V(\mathbf{r}_{B/P}) = \frac{\mathbf{m} \cdot \mathbf{r}_{B/P}}{|\mathbf{r}_{B/P}|^3} \quad (3)$$

with the dipole vector being defined in Earth fixed frame \mathcal{E} coordinates as

$$\mathbf{m} = {}^{\mathcal{E}} \begin{bmatrix} g_1^1 \\ h_1^1 \\ g_1^0 \end{bmatrix} \quad (4)$$

The magnetic field vector \mathbf{B} is expressed at the spacecraft location as

$$\mathbf{B}(\mathbf{r}_{B/P}) = -\nabla V(\mathbf{r}_{B/P}) = \frac{3(\mathbf{m} \cdot \mathbf{r}_{B/P})\mathbf{r}_{B/P} - \mathbf{r}_{B/P} \cdot \mathbf{r}_{B/P}\mathbf{m}}{|\mathbf{r}_{B/P}|^5} = \frac{1}{|\mathbf{r}_{B/P}|^3} (3(\mathbf{m} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}) \quad (5)$$

where

$$\hat{\mathbf{r}} = \frac{\mathbf{r}_{B/P}}{|\mathbf{r}_{B/P}|} \quad (6)$$

The above vector equation is evaluated in \mathcal{E} -frame components, while the output is mapped into \mathcal{N} -frame components by returning

$${}^{\mathcal{N}}\mathbf{B} = [EN]^T {}^{\mathcal{E}}\mathbf{B} \quad (7)$$

2 Module Functions

This module will:

- **Compute magnetic field vector:** Each of the provided models is fundamentally intended to compute the planetary magnetic vector for a spacecraft.
- **Subscribe to model-relevant information:** Each provided magnetic field model requires different input information to operate, such as spacecraft positions or time. This module automatically attempts to subscribe to the relevant messages for a specified model.
- **Support for multiple spacecraft and model types** Only one magnetic field module is required for each planet, and can support an arbitrary number of spacecraft. Output messages for individual spacecraft are automatically named based on the environment type.

3 Module Assumptions and Limitations

Individual magnetic field models are complex and have their own assumptions. The reader is referred to the cited literature to learn more about the model limitations and challenges.

4 Test Description and Success Criteria

This section describes the specific unit tests conducted on this module.

This unit test only runs the magnetic field Basilisk module with two fixed spacecraft state input messages. The simulation option `useDefault` checks if the default atmosphere parameters for an Earth-based centered dipole module are used, or if the exponential model information is setup manually. The option `useMinReach` dictates if the minimum orbit radius check is performed, while the option `useMaxReach` checks if the maximum reach check is performed. The option `usePlanetEphemeris` checks if a planet state input message should be created. All permutations are checked.

5 Test Parameters

The simulation tolerances are shown in Table 2. In each simulation the neutral density output message is checked relative to python computed true values.

Table 2: Error tolerance for each test.

Output Value Tested	Tolerated Error
magneticField vector	1e-05 (relative)

6 Test Results

The following two tables show the test results. All tests are expected to pass.

Table 3: Test result for `test_unitTestMagneticField.py`

useDefault	useMinReach	useMaxReach	usePlanetEphemeris	Pass/Fail
False	False	False	False	PASSED
False	False	False	True	PASSED
False	False	True	False	PASSED
False	False	True	True	PASSED
False	True	False	False	PASSED
False	True	False	True	PASSED
False	True	True	False	PASSED
False	True	True	True	PASSED
True	False	False	False	PASSED
True	False	False	True	PASSED
True	False	True	False	PASSED
True	False	True	True	PASSED
True	True	False	False	PASSED
True	True	False	True	PASSED
True	True	True	False	PASSED
True	True	True	True	PASSED

7 User Guide

7.1 General Module Setup

This section outlines the steps needed to add a `MagneticField` module to a sim. First, the planet magnetic field model must be imported and initialized:

```
from Basilisk.simulation import magneticField
magModule = magneticField.MagneticField()
magModule = "magneticFieldModel"
```

By default the model assumes a centered magnetic dipole model about the Earth using IGRF 2020 coefficients.

Optionally, if a different model type is required, the desired model type must be set by calling "setEnvType":

```
magModule.setEnvType(magneticField.MODEL_CENTERED_DIPOLE)
```

The model can then be added to a task like other simModels. Each MagneticField module calculates the magnetic field based on the output state messages for a set of spacecraft.

To add spacecraft to the model the spacecraft state output message name is sent to the addScToModel method:

```
scObject = spacecraftPlus.SpacecraftPlus()
scObject.ModelTag = "spacecraftBody"
magModule.addSpacecraftToModel(scObject.scStateOutMsgName)
```

7.2 Planet Ephemeris Information

The optional planet state message name can be set by directly adjusting that attribute of the class:

```
magModule.planetPosInMsgName = "PlanetSPICEMsgName"
```

If SPICE is not being used, the planet is assumed to reside at the origin and $r_{P/O} = 0$.

7.3 Setting the Model Reach

By default the model doesn't perform any checks on the altitude to see if the specified magnetic field model should be used. This is set through the parameters envMinReach and envMaxReach. Their default values are -1. If these are set to positive values, then if the spacecraft orbit radius is smaller than envMinReach or larger than envMaxReach, the magnetic field vector is set to zero.

7.4 Centered Dipole Magnetic Field User Guide

If the module's envType is set to magneticField.MODEL_CENTERED_DIPOLE, the parameters of the dipole model can be set by calling

```
magModule.dipoleParams.g10 = g10Value
magModule.dipoleParams.g11 = g11Value
magModule.dipoleParams.h11 = h11Value
```

where g_1^0 , g_1^1 and h_1^1 are the first three expansion terms of the IGRF spherical harmonics model.*

The python support file simSetPlanetEnvironment.py contains a helper function called

```
centeredDipoleMagField()
```

which helps setup common NASA centered dipole models for a range of planets that contain global magnetic fields. This possible planet names includes mercury, earth, jupiter, saturn, uranus and neptune. The function is then called with

```
simSetPlanetEnvironment.centeredDipoleMagField(testModule, "jupiter")
```

to setup the named planets dipole model.

* <https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>

REFERENCES

- [1] Hanspeter Schaub and John L. Junkins. *Analytical Mechanics of Space Systems*. AIAA Education Series, Reston, VA, 4th edition, 2018.
- [2] F. Landis Markley and John L. Crassidis. *Fundamentals of Spacecraft Attitude Determination and Control*. Springer, New York, 2014.
- [3] Michael D. Griffin and James R. French. *Space Vehicle Design*. AIAA Education Series, Reston, VA, 2005.
- [4] David Vallado. *Fundamentals of Astrodynamics and Applications*. Microcosm press, 4 edition, 2013.