Autonomous Vehicle Simulation (AVS) Laboratory, University of Colorado

Basilisk Technical Memorandum

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MAGNETIC FIELD ENVIRONMENT – WORLD MAGNETIC MODEL (WMM)

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Status: Released
Scope/Contents
The `MagneticFieldWMM` class is used to calculate the magnetic field vector above the Earth using the World Magnetic Model (WMM). 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. Earth magnetic field parameters are read in from the WMM coefficient file.

Rev	Change Description	By	Date
1.0	Initial release	H. Schaub	06-27-2019

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1 Model Description

1.1 General Module Behavior

The purpose of this WMM magnetic field module is to implement a magnetic field model that rotates with an Earth-fixed frame $\mathcal{P} : \{\hat{\boldsymbol{p}}_1, \hat{\boldsymbol{p}}_2, \hat{\boldsymbol{p}}_3\}$. Note that this model is specific to Earth, and is not applicable to other planets. The Earth-fixed frame has $\hat{\boldsymbol{p}}_3$ being the typical positive rotation axis and $\hat{\boldsymbol{p}}_1$ and $\hat{\boldsymbol{p}}_2$ span the Earth's equatorial plane where $\hat{\boldsymbol{p}}_1$ points towards the prime meridian.

`MagneticFieldWMM` is a child of the `MagneticFieldBase` base class and provides an Earth specific magnetic field model based on the World Magnetic Model. By invoking the magnetic field module, the default epoch values are set to the BSK default epoch value of Jan 01 2019 00:00:00. 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 magnetic 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.

1.2 Planet Centric Spacecraft Position Vector

For the following developments, the spacecraft location relative to the planet frame is required. Let $\boldsymbol{r}_{B/P}$ 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

$$\boldsymbol{r}_{B/P} = \boldsymbol{r}_{B/O} - \boldsymbol{r}_{P/O} \tag{1}$$

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

If no planet ephemeris message is specified, then the planet position vector $\boldsymbol{r}_{P/O}$ is set to zero.

Let $[PN]$ be the direction cosine matrix[1] that relates the rotating planet-fixed frame relative to an inertial frame $\mathcal{N}: \{\hat{\boldsymbol{n}}_1, \hat{\boldsymbol{n}}_2, \hat{\boldsymbol{n}}_3\}$. 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

$$ {}^{\mathcal{P}}\boldsymbol{r}_{B/P} = [PN]\, {}^{\mathcal{N}}\boldsymbol{r}_{B/P} \tag{2} $$

1.3 World Magnetic Model — WMM

The World Magnetic Model (WMM) is a large spatial-scale representation of the Earth's magnetic field. It consists of a degree and order 12 spherical harmonic expansion of the magnetic potential of the geomagnetic main field generated in the Earth's core. Apart from the 168 spherical-harmonic "Gauss" coefficients, the model also has an equal number of spherical-harmonic Secular-Variation (SV) coefficients predicting the temporal evolution of the field over the upcoming five-year epoch.

Updated model coefficients are released at 5-year intervals, with WMM2015 (released Dec 15, 2014) supposed to last until December 31, 2019. However, due to extraordinarily large and erratic movements of the north magnetic pole, an out-of-cycle update (WMM2015v2) was released in February 2019 (delayed by a few weeks due to the U.S. federal government shutdown) to accurately model the magnetic field above 55°north latitude until the end of 2019. The next regular update (WMM2020) will occur in late 2019.

The WMM magnetic vector $\boldsymbol{B}$ is evaluated in a local North-East-Down (NED) frame $\mathcal{M}$-frame. Let ϕ and λ be the local latitude and longitude of the spacecraft location relative the Earth-fixed frame $\mathcal{P}$. The DCM mapping from $\mathcal{M}$ to $\mathcal{P}$ is

$$ [PM] = [M_3(-\lambda)][M_2(\phi + \frac{\pi}{2})] \tag{3} $$

The $\boldsymbol{B}$ vector is mapped into $\mathcal{N}$-frame components by returning

$$ {}^{\mathcal{N}}\boldsymbol{B} = [PN]^T [PM]\, {}^{\mathcal{M}}\boldsymbol{B} \tag{4} $$

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

This WMM field is specific to the Earth, and valid for a 5 year duration. See the WMM documentation on more information on this model.

4 Test Description and Success Criteria

The WMM software provides a PDF with 12 sample locations and magnetic field values that should be returned in the NED frame. The unit test runs the magnetic field Basilisk module with two fixed spacecraft state input messages. Their locations are identical and set to the WMM test locations. The simulation option `useDefault` checks if the module epoch time value default settings are used, or if the epoch time in terms of a decimal year is specified directly. The option `useMsg` determines if the epoch time is read in through a message. If this message is available, it is supposed to over-rule the epochYear variable. 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`	0.1 (nT, relative)

6 Test Results

Over 200 test permutations are run by the unit test. All are expected to pass.

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 magneticFieldWMM
magModule = magneticFieldWMM.MagneticFieldWMM()
magModule.ModelTag = "WMM"
magModule.dataPath = splitPath[0] + 'Basilisk/supportData/MagneticField/'
```

By default the model assumes the BSK epoch date and time. To set a common epoch time across various BSK modules, then the `EpochMsgPayload` must be created and written.

```
epochMsgData = messaging.EpochMsgPayload()
dt = unitTestSupport.decimalYearToDateTime(decimalYear)
epochMsgData.year = year
epochMsgData.month = month
epochMsgData.day = day
epochMsgData.hours = hour
epochMsgData.minutes = minute
epochMsgData.seconds = second
epMsg = messaging.EpochMsg().write(epochMsgData)
magModule.epochInMsg.subscribeTo(epMsg)
```

If the user wants to set the WMM epoch directly, this is done by defining the `epochDate` variable in terms of a decimal year format required by WMM.

```
magModule.epochDate = decimalYear
```

Not that the epoch message, if available, over-writes the information of setting `epochDate`.

The model can be added to a task like other simModels.

```
unitTestSim.AddModelToTask(unitTaskName, testModule)
```

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 = spacecraft.Spacecraft()
scObject.ModelTag = "spacecraftBody"
magModule.addSpacecraftToModel(scObject.scStateOutMsg)
```

7.2 Planet Ephemeris Information

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

```
magModule.planetPosInMsg.subscribeTo(planetMsg)
```

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

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.

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. Grifin and James R. French. *Space Vehicle Design*. AIAA Education Series, Reston, VA, 2005.