SOFTWARE TESTING OF AN AUTONOMOUS REDUNDANT ATTITUDE DETERMINATION SYSTEM FOR CUBESATS

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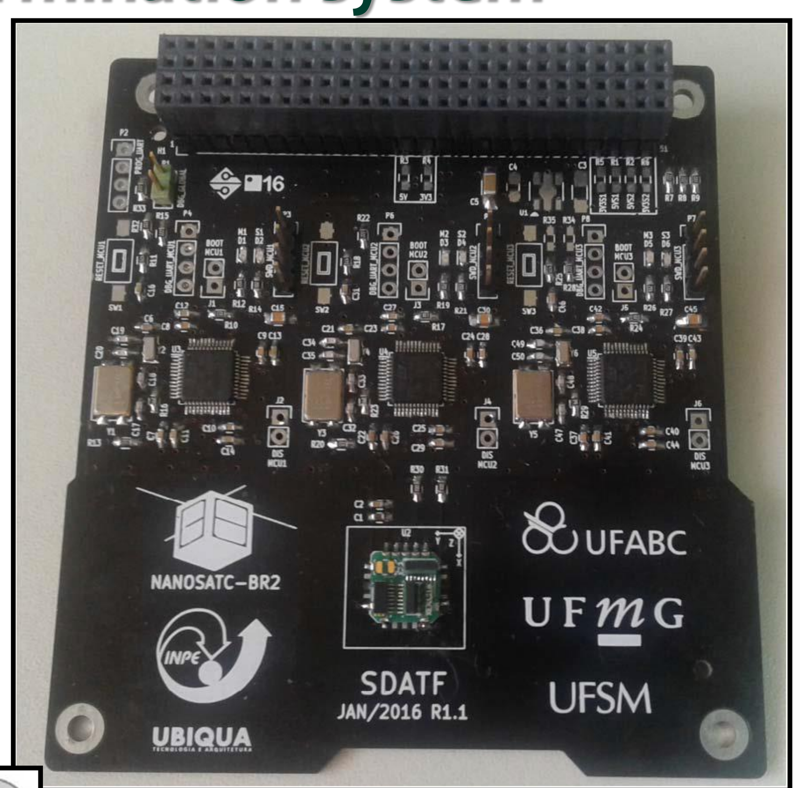
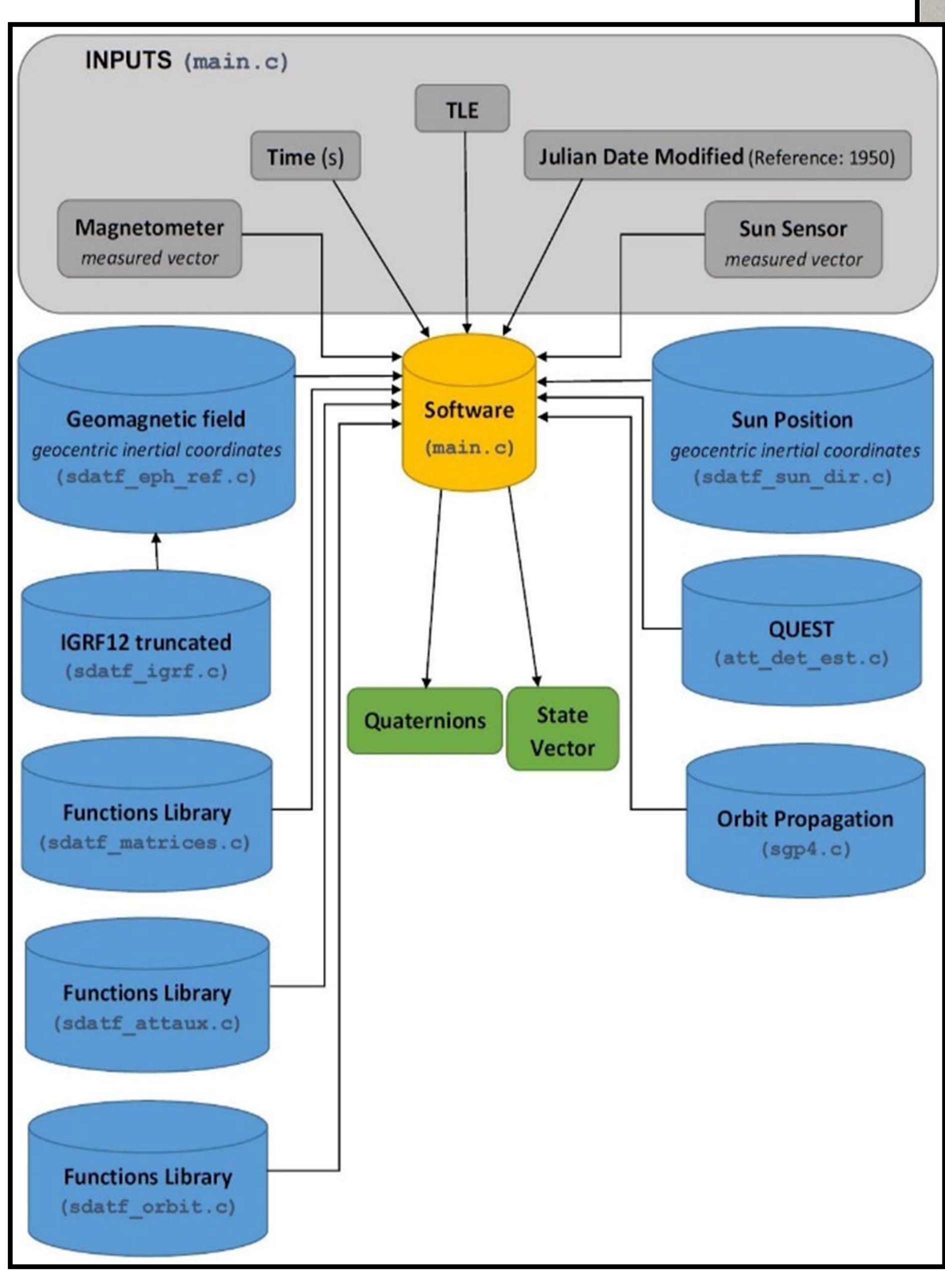
Introduction

- Software testing procedures and their results concerning the development of an autonomous redundant attitude determination system for nanosatellites.
- Fault Tolerant Attitude Determination System (SDATF) is the first attitude determination system with triple redundancy developed by UFMG and UFABC in partnership with the Brazilian Institute for Space Research (INPE).
- SDATF is planned to have a flight validation as payload of the NanosatC-BR2 (NCBR2, INPE).
- The program aims to prepare human resources for R&Din space instrumentation, stimulate the space technology themes in universities and companies, and open access opportunities to space for scientific experiments.

Fault tolerant attitude determination system

- The SDATF is an integrated circuit board composed of 3 microcontrollers (MCU) STM32F303CC ARM Cortex-M4F, 3 magnetometers XEN 1210. NanoSatC-BR2 is equipped with 6 Sun sensors one on each face, which provides the sun position. The communication between the micro-controllers and On-Board Computer (OBC) occurs through channel I2C, and all microcontrollers contain the full software package and work together in a redundant manner to identify when a fault occurs.



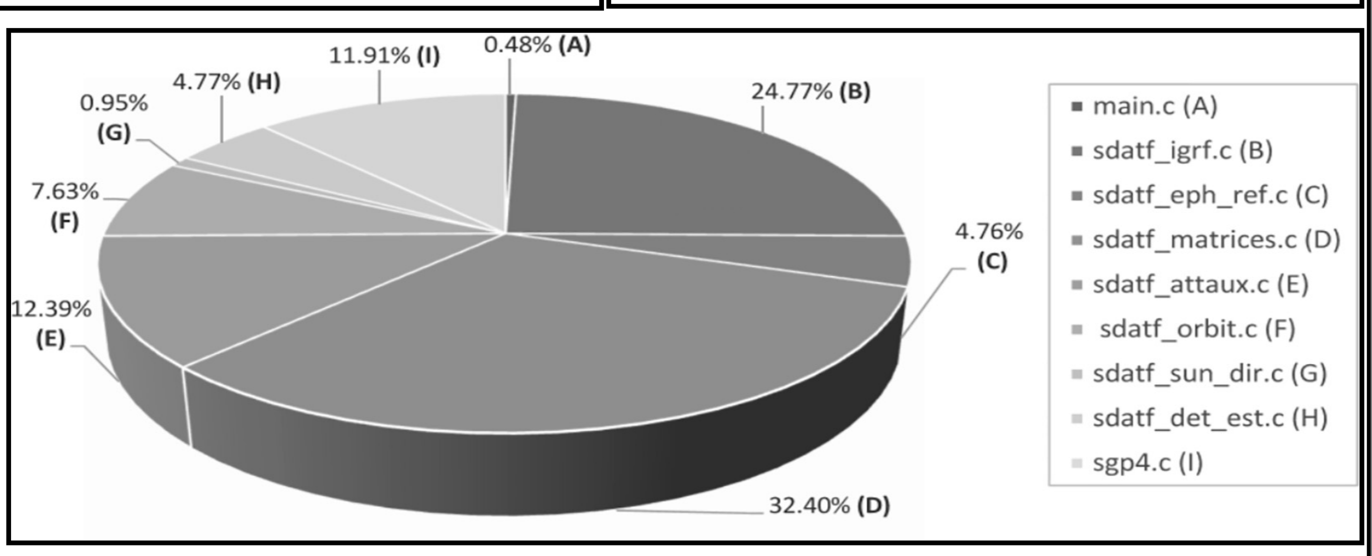


Software architecture

- The embedded software has the main task of calculating the attitude of the nanosatellite. The software architecture is composed of several modules.

Execution time in each Module.

Module	Seconds
main.c	0.01
sdatf_igrf.c	0.26
sdatf_eph_ref.c	0.05
sdatf_matrices.c	0.34
sdatf_attaux.c	0.13
sdatf_orbit.c	0.09
sdatf_sun_dir.c	0.01
sdatf_det_est.c	0.05
sgp4.c	0.13
Total	1.07



Percentage of the total running time for each module.

Mathematical models

- The SDATF requires the knowledge of two vectors, the Sun position and the geomagnetic field. They are obtained using mathematical models described below.

Sun position vector

- The computation needs two inputs: the Modified Julian Day (MJD) and the fraction of the day (fd) in seconds. The MJD starts in Jan 1, 1950 at midnight (UTC). This model is valid from Jan 1, 2000 until 2050. The starting point of the day number (d) is January 1, 2000 (0.0 UTC). The Sun position vector in geocentric equatorial coordinates is given by:

$$x = r\cos\lambda_{ecliptic} \qquad y = r\sin\lambda_{ecliptic}\cos\epsilon \qquad z = r\sin\lambda_{ecliptic}\sin\epsilon$$

- The origin of this system is at the Earth's center. The x-axis points to the vernal equinox, the z-axis points to the North Pole and the y-axis completes the trihedron. The Sun-Earth distance (r) is equal to one Astronomical Unit (AU). Other models: Vallado (1997) and Astronomical Almanac model (2014). The NanosatC-BR2 model is adequate to the required accuracy.

Magnetic field vector

- The International Geomagnetic Reference Field (IGRF) is a series of models that describe the Earth's Magnetic Field. The IGRF12 is the version released by the International Association of Geomagnetism and Aeronomy (IAGA) in December 2014, suited up to 2020. The magnetic field (B) on the Earth's surface and above it can be written in terms of the scalar potential V: $\vec{B} = -\nabla V$
- In spherical polar coordinates, V can be approximated by the following finite series:

$$V(r,\theta,\phi,t) = a\sum_{n=1}^{N}\left(\frac{a}{r}\right)^{n+1}\sum_{m=0}^{n}\left[g_n^m(t)\cos(m\phi) + h_n^m(t)\sin(m\phi)\right]P_n^m(\theta)$$

where r is the radial distance from the center of the Earth, a is the Earth's mean reference radius, θ is the colatitude and φ is the east longitude from Greenwich Meridian. The functions $P_n^m(\theta)$ are the Schmidt quasi-normalized associated Legendre function. The maximum degree and order proposed by the original model is 13. And g_n^m and h_n^m are the Gauss coefficients.

Attitude determination

- The adopted algorithm for the attitude determination is the well-know QUEST method (Shuster and Oh, 1981). $L(A) = \frac{1}{2}\sum_{i=1} a_i(\hat{w}_i - A\hat{v}_i)^2$
- Steps for attitude determination: (1) calculate Greenwich Meridian Sideral Time (GMST), (2) calculate the satellite position vector $P_{inertial}$ in Geocentric Inertial coordinates, (3) transformation of $P_{inertial}$ in Geocentric Terrestrial Cartesian coordinates, (4) transform it in Geocentric spherical coordinates, (5) calculate the inputs of IGRF12 truncated model (geomagnetic field), (6) calculate the geomagnetic field using IGRF12, (7) transform this field from NED to Geocentric Terrestrial coordinates, (8) transform it to Geocentric cartesian coordinates, (9) normalize the geomagnetic field vector in the body frame wm and in inertial frame vm, (10) calculate the Sun position vector vs, (11) determine the attitude quaternion using QUEST, wm, vm, ws, vs.

Software validation tests results

Table 5
Error analysis results: comparison between models.

Type of errors	NanosatC-Br2 vs Vallado's Model	NanosatC-Br2 vs Astr. Almanac 2015
Min. absolute magnitude error (%)	0.00	0.00
Max. absolute magnitude error (%)	1.70	1.80
Average absolute magnitude error (%)	1.06	1.07
Min. angle error (Deg)	0.01	0.00
Maximum angle error (Deg)	0.01	0.01
Average angle error (Deg)	0.01	0.01
Standard deviation of angle error (Deg)	5.02E−04	7.35E−04

Table 7
Comparison in terms of execution time.

Execution time	NanosatC-BR2	Vallado's model	Astr. Almanac 2015
Average (s)	0.128	0.129	0.132
Minimum (s)	0.109	0.109	0.109
Maximum (s)	0.140	0.141	0.156
Standard deviation (s)	7.21E−03	8.39E−03	9.68E−03

Table 8
Comparison in terms of memory.

Memory	NanosatC-BR2	Vallado's model	Astr. Almanac 2015
Size (bytes)	91,469	92,799	91,748
Commit (KB)	412	444	396
Working set (KB)	1724	1732	1708

Table 9
Error analysis results: comparison between the analyses.

Type of errors	Analysis 1	Analysis 2
Max. absolute magnitude error (%)	2.80	3.10
Min. absolute magnitude error (%)	0.03	0.00
Average absolute magnitude error (%)	0.50	0.62
Maximum angle error (Deg)	1.60	1.53
Minimum angle error (Deg)	0.03	0.01
Average angle error (Deg)	0.50	0.42
Standard deviation of angle error (Deg)	3.09E−01	2.66E−01

- Sun position vector: NanoSatC-BR2 model ompared to low precision models (Vallado, Astronomical Almanac model, Systems Tool Kit/STK). The Average Absolute Magnitude Error of NanosatC-BR2 model differs 1% from the others. The Average Angle Error and the Maximum Angle error of Nanosatc-Br2 in comparison Vallado's and Astronomical Almanac Model is 0.01° , and standard deviation close to zero.
- Magnetic field vector: NanoSatC-BR2 utilizes a truncated version of IGRF12 (N=5). Results of both analyses are not so different. Average Absolute Magnitude Error of the first analysis is 0.50%, while the Average Absolute Magnitude Error of the second analysis is 0.62%. Analysis 1 provided an average angle error of 0.5° , Analysis 2 provides an average angle error of 0.42° .

Conclusion

- Adopted model obtains the Sun position vectors in the inertial frame with an average angle error lower than 1° , and the average magnitude error was approximately 1% in comparison with the other two models, and also in comparison with STK results.
- Truncated IGRF12 model (N=5) for the geomagnetic field obtained satisfactory results in comparison with the original IGRF12 (N=13). Average absolute magnitude errors: 0.5% and 0.62% for two analyses. Average angle error: 0.5° and 0.42° for two analyses.

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Main reference: Garcia; Vale; Martins-Filho; Duarte; Kuga; Carrara. *Validation tests of attitude determination software for nanosatellite embedded systems.* MEASUREMENT. v. 116, p. 391, 2017