X Workshop em Engenharia e Tecnologia Espaciais
7 a 9 de agosto de 2019

Use of Artificial Neural Networks in Satellite Simulators

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Abstract. *Satellite operational simulator is a tool used to support the operation of a satellite. In this paper an Artificial Neural Network (ANN) was used to design models that describe parts of a satellite's Electrical Power Supply Subsystem. The results are compared with previous research using an identification technique called n4sid and with the real telemetry values of the CBRS-4 satellite. The Artificial Neural Network produced better results, for all EPSS parameters (battery voltage, main error amplifier voltage and battery discharge regulator current) identified, than the n4sid identification. The models implemented with ANN shown to be sufficiently accurate for use in a satellite operational simulator.*

Palavras-chave: Artificial Neural Network, Electrical Power Supply Subsystem, System Identification, Space System Simulation.

1. Introduction

The Low Earth Orbit (LEO) satellites must have a subsystem capable of providing the energy necessary for their operation. Generally, this subsystem, known as Electrical Power Supply Subsystem (EPSS or EPS), has the following features: supply, control, storage and distribution of electricity for satellite loads. [Wertz and Larson 1999]

The EPSS is responsible for 41% of failures after 5 years of operation, and catastrophic failure can cause loss of mission. [Castet and Saleh 2009, Kim et al. 2011, Kim et al. 2012, Magalhães 2012]

After the launch of the satellite, a satellite operational simulator can be used to anomaly investigation and resolution that can happen due to the aging of the subsystem [ECSS 2010]. In general, the EPSS model executed by the simulator should reproduce the health status of the satellite with a high level of accuracy.

In order to obtain more accurate models, this paper proposes the use of artificial neural networks. The results will be compared with the previous work that used an identification technique known as numerical algorithms for subspace state space system identification (N4SID) [Rodrigues et al. 2018].

Identification techniques have been used for a long time in the space area as suggested by [Campion et al. 1982, Adachi et al. 1999].

The main contribution of this paper is the experimental use of neural networks to better understand the behavior of some EPSS pieces of equipment of the CBERS-4 satellite.

The remainder of this paper is organized as the following. Section 2 presents the problem that the paper proposes to solve by using ANN. Section 3 gives a brief description of a back-propagation neural network. Section 4 describes the methodology for applying the ANN. The results are presented in Section 5 comparing the results produced by the model using ANN the results produced by the model using the `n4sid`. In section 6 the conclusions are presented.

2. Problem Statement

The China-Brazil Earth Resources Satellite (CBERS) Program is a mutual technological effort between Brazil and China, established more than 30 years ago, in order to develop satellites Earth observation satellites [CBERS 2018a, CBERS 2018b].

The control of the satellite in orbit is done by the satellite control center. To support the operation team, the operational simulator is used to: (i) to develop and validate the flight control procedures, (ii) to train the operations team, (iii) to validate the satellite control center software, and (iv) to support the troubleshooting and maintenance [Ambrosio et al. 2006, Eickhoff 2009, ECSS 2010].

The SimCBERS Simulator, released in 2017, is the operational simulator for CBERS-4. The SimCBERS simulates the 15 subsystems of CBERS-4, performs the orbit propagation, the space environmental conditions and the ground stations. The subsystems (models in XML) were modeled using the behavioral model approach described in [Tominaga et al. 2012].

One of the subsystems implemented in SimCBERS is the EPSS. The CBERS-4 EPSS is composed of the following equipment: solar generator (SAG), divided into two sections (SAG1 and SAG2), batteries (BAT1 and BAT2), shunt regulator (SHUNT), batteries discharge regulator (BDR) and the continuous voltage converters (DC/DC). The equipment, illustrated in Figure 1, are described in Table 1

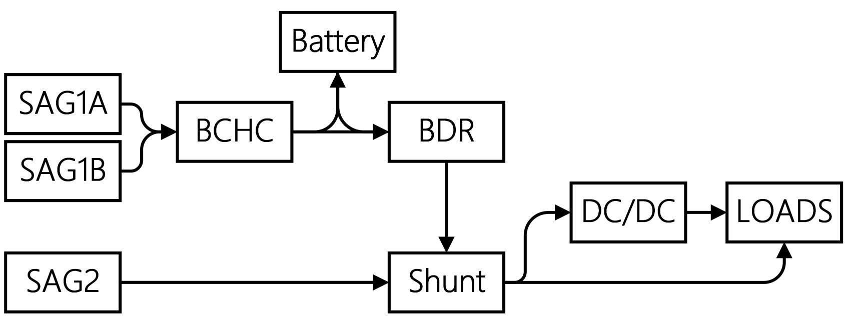

Figure 1. EPSS Diagram Block. [Rodrigues et al. 2018]

Table 1. Description of the main EPSS equipment. [Magalhães 2005, Magalhães 2012, Torres 2014, Magalhães 2014, Torres 2014, Rodrigues et al. 2018]

Equipment	Description
SAG	The energy from the solar cells is distributed for: (i) charging the batteries, via SAG1 divided into SAG_{1A} and SAG_{1B} circuits, to each battery, also (ii) for direct energy transferring to the satellite loads, by SAG_2.
SHUNT	The Shunt is composed of six switched channels, a capacitor bank and a main error amplifier (MEA). These channels are controlled by MEA, receive the energy from SAG_2 and they delivery to the main bus. The MEA verifies the main bus voltage and controls the opening or closure of the shunt channels, keeping the main bus voltage constant.
BAT	Batteries are elements that store energy. They are recharged during the period of sunlight and discharged during the eclipse of the satellite.
BDR	The BDR (Battery Discharge Regulator) is composed of: battery switched regulators (BSR), two redundant battery charge controllers (BCC) and two redundant battery heat controllers (BHC). The BSR keeps the battery voltage regulated. The BCCs, one for each battery, are responsible for the battery charge and depend on the battery temperature and voltage. The BHCs, also having one for each battery, are responsible for the heat control and actuate in the heaters located above the batteries.
DC/DC	The DC/DC converters are responsible the main bus voltage to smaller regulated voltages, when the loads of the satellite are not connected to the main bus.

In order to avoid a risky operation for the mission it is essential to have reliable models to run the simulations in the optional simulator. A study conducted by [Rodrigues et al. 2018] investigated the use of an identification technique to obtain more accurate models.

The model of EPSS considers the behavior, which depends on the telecommands [Tominaga et al. 2012], and its dynamics, described with mathematical equations [Magalhães 2009, Torres et al. 2010, Magalhães and Silva 2017]. The Table 2 shows the SimCBERS errors (see Equation 2) using mathematical models [Rodrigues et al. 2017] and the identified models [Rodrigues et al. 2018], compared to real telemetry, for the following parameters: V_{BAT1}, I_{BDROUT} and V_{MEA}.

Table 2. Comparison between mathematical models and identified models. [Rodrigues et al. 2018]

Parameter	Mathematical Model	Identified Model
V_{BAT1}	3.3%	2.25%
I_{BDROUT}	16.4%	11.75%
V_{MEA}	Not implemented	13.48%

In order to minimize the error of the operational simulator in relation to the satellite, other approaches can be investigated. In this paper a test is performed using artificial neural networks (ANN) to learn the behavior of the parameters presented in Table 2.

The ANN have been showing success in several applications in the space area, such as: thermal [Reis Júnior et al. 2016], spacecraft power system controller [El-madany et al. 2011], battery degradation [Donato 2018], satellite bus voltage [Ibrahim et al. 2018]. In addition, the use of ANN is a trend for satellite control centers as shown by [Li 2017, Kolbeck et al. 2018, O'Meara and Wickler 2018]

3. Feed-Forward Artificial Neural Network (ANN)

The Figure 2 presents the architectural of a multiplayer perceptron (MLP). MLP networks basically have two types of signal [Haykin 2005, Haykin 2009]:

- Inputs: propagates forward through the network and emerges at the output end of the network as an output signal. Contains samples used to train and excite the ANN.
- Error signal - an error signal, Equation 1, originates at an output neuron of the network and propagates backward (layer by layer) through the network. Through the error backpropagation the ANN weights are adjusted.

$$E = \frac{1}{2} \sum_j (y_j - d_j)^2 \tag{1}$$

Where y represents the ANN output and d the desired output, given by online measurements.

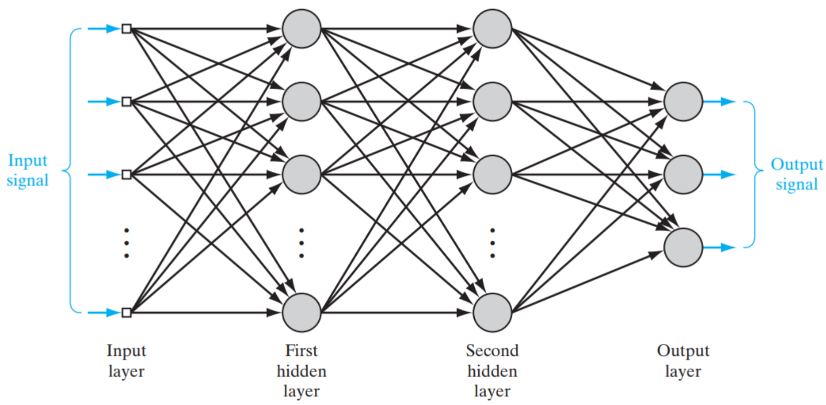

Figure 2. Architectural of a multilayer perceptron with two hidden layers and three outputs. [Haykin 2009]

4. Methodology

The methodology described in [Rodrigues et al. 2018] is reproduced in this paper, as follows:

- Samples: the data used for training the network are the same as those used in previous work.
- ANN: the equipment model is obtained from the ANN application. The ANN used was `feedforwardnet` provide by MATLAB.
- Results: the network outputs are compared to real telemetry, using the mean relative square error (MRSE), defined in Equation 2. [Borjas and Garcia 2011, Vazan et al. 2017, Rodrigues et al. 2018]

$$MRSE(\%) = \frac{1}{no}\sum_{q=1}^{no}\left[\sqrt{\frac{\sum_{t=1}^{val}(y_q(t)-\hat{y}_q(t))^2}{\sum_{t=1}^{val}\hat{y}_q(t)^2}}\right]100 \quad (2)$$

where y_q(t) is the q-th real output data (real telemetry), $\hat{y}_q$(t) is the q-th estimated output data (ANN output), no is the total number of outputs and val is the amount of data used to measure the performance of the ANN.

The ANN `feedforwardnet` was configured with the following number of neurons in the hidden layer:

- $V_{BAT1} \rightarrow$ 4 neurons;
- $I_{BDROUT} \rightarrow$ 4 neurons;
- $V_{MEA} \rightarrow$ 4 neurons.

As for the identification, for the training of the neural networks the same inputs were also used for each one of the parameters, as follows:

- $V_{BAT1} \rightarrow$ 4 inputs: the battery current (I_{BAT1}), the solar array current (I_{SAG1A}), the current supplied by solar array for the battery (I_{SGBCHC}) and the bus voltage (V_{BUS});
- $I_{BDROUT} \rightarrow$ 2 inputs: the BDR input currents, I_{BDRIN1} and I_{BDRIN2};
- $V_{MEA} \rightarrow$ 4 inputs: the BDR output current (I_{BDROUT}), the solar array current (I_{SG2}), the bus current (I_{BUS}) and the bus voltage (V_{BUS}).

It is important to note that the ANN used the same amount of sample used by the identification technique.

5. Results and discussion

Table 3 shows the parameter MRSE. A decrease in error is observed for all parameters. Figures 3 to 5 show the graphical comparison which demonstrate that the behavior of the EPSS parameters are consistent with the actual telemetry.

Table 3. MRSE for ANN.

Parameter	ANN
V_{BAT1}	1.56%
I_{BDROUT}	10.76%
V_{MEA}	0.41%

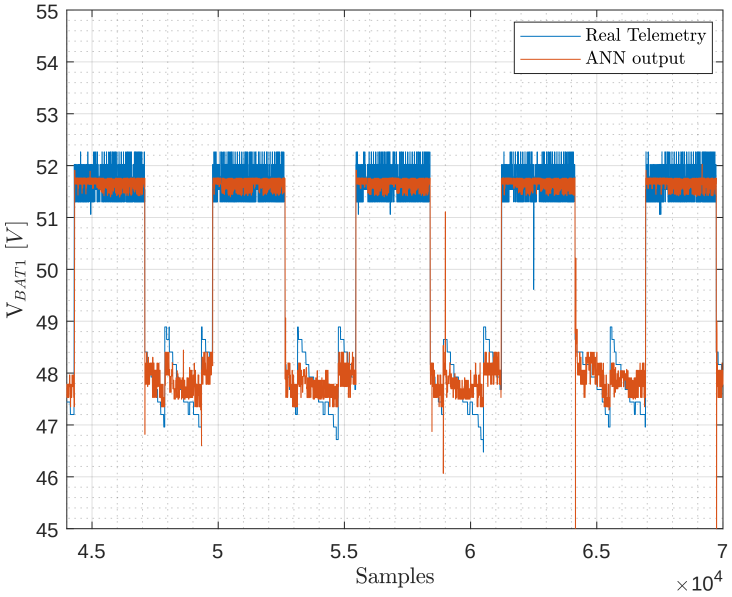

Figure 3. V$_{BAT1}$ comparison.

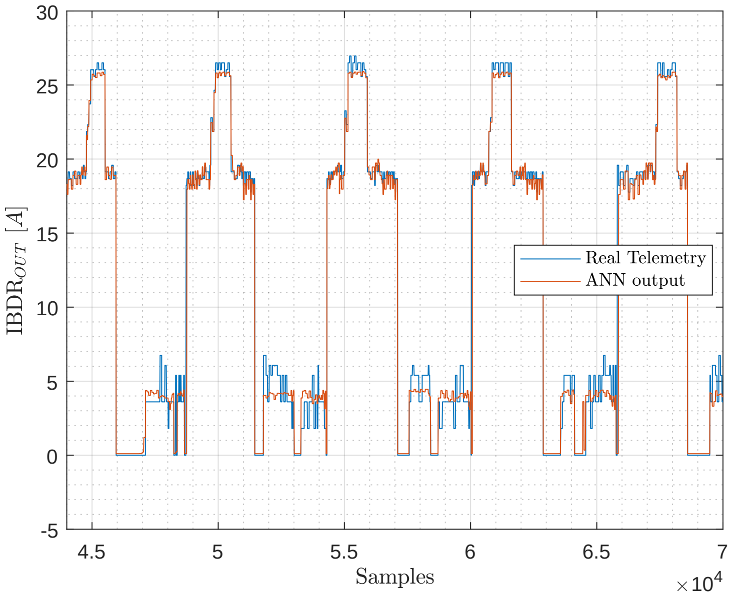

Figure 4. I$_{BDROUT}$ comparison.

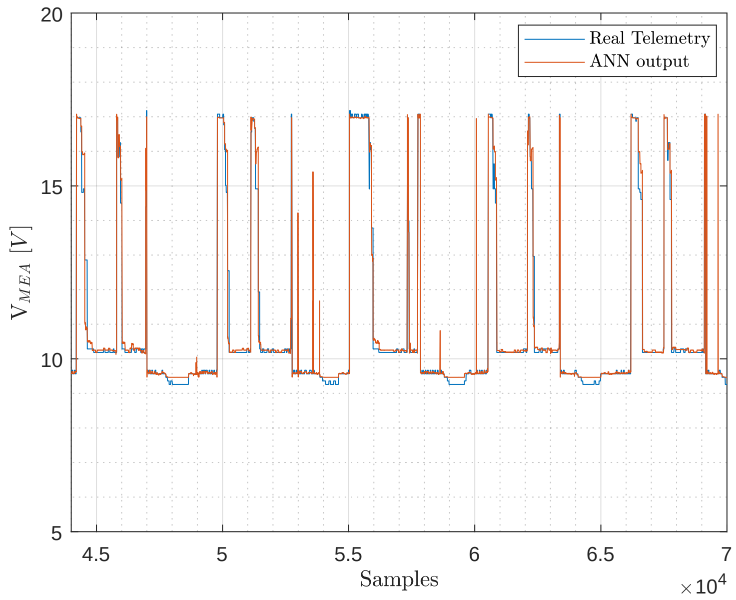

Figure 5. V$_{MEA}$ comparison.

Note that the error, both in the identified model and in the ANN, was smaller than the error of the mathematical model implemented in the simulator. It can be assumed that this error is smaller because actual measurement data is used, which includes subsystem degradation.

Figure 6 shows the difference between the errors of each model.

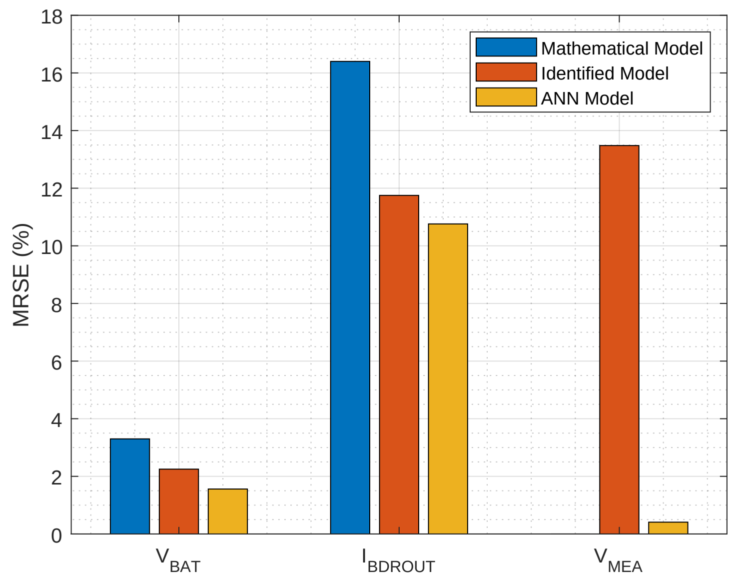

Figure 6. Comparison between the three models.

6. Conclusion

The use of ANN showed to be quite effective for obtaining accurate models of satellite subsystems, in particular for EPSS.

The ANN had more advantages because the error was the smallest, when compared to the error of the mathematical model implemented in the simulator and the error obtained by the identification technique, was the smallest of all.

As future research we propose to increase the number of samples for training, since in this paper we used the same sampling used of the identification technique (`n4sid`); to evaluate the influence of the correlation between CBERS-4 telemetry.

Acknowledgments: *The authors would like to thank INPE for the opportunity to carry out this work and CAPES (Coordination for the Improvement of Higher Education Personnel) for the financial support.*

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