IDENTIFICATION AND CONTROL TECHNIQUES APPLIED TO AN OPERATIONAL SATELLITE SIMULATOR

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Abstract— Operational satellite simulators are mainly used for training operators and validating operational procedures, requiring reasonable level of fidelity in the simulated satellite telemetry. In this paper we propose the use of the subspace identification method to improve a higher level of fidelity of the model representing the CBERS-4 Electrical Power Supply Subsystem. We adopted the identification method known as n4sid to identify a state space model for real equipment of such Subsystem. To reduce the error of the identified model it is also proposed the application of two control actions, pole placement and pole placement with integral feedback. The obtained results were satisfactory, that is, in relation to the real telemetry, the identified models presented a margin of error smaller than the models currently implemented in the simulator.

Keywords— Identification method, CBERS, Satellite Operational Simulator, Electrical Power Supply.

Resumo— Simuladores Operacionais de Satélites são utilizados principalmente para treinamento da equipe de operadores e para validação de procedimentos operacionais do satélite após seu lançamento. Dessa forma, as simulações devem prover resultados com um razoável nível de fidelidade. Neste artigo propomos o uso de identificação por métodos de subespaço para obtenção de modelos que representem o subsistema de fornecimento de energia do satélite CBERS-4 com um alto nível de fidelidade. Foi adotado o método de identificação conhecido como n4sid para identificar o modelo em espaço de estados de alguns equipamentos do subsistema. Para reduzir o erro do modelo identificado também é proposto a aplicação de duas ações de controle: alocação de polos e alocação de polos com realimentação integral. Os resultados obtidos foram satisfatórios, isto é, em relação as telemetrias reais, os modelos identificados apresentaram uma margem de erro menor que os modelos implementados atualmente no simulador.

Palavras-chave— Método de identificação, CBERS, Simulador Operacional de Satélite, Subsistema de Fornecimento de Energia.

1 Introduction

An operational satellite simulator is used in space mission to perform, during satellite operation, the following functions: (i) to develop and validate the flight control procedures, (ii) to train the flight control team, (iii) to validate the satellite control center software and (iv) to support the troubleshooting and maintenance (Eickhoff, 2009; ECSS, 2010). In Brazil, the National Institute for Space Research (INPE) has developed an operational satellite simulator for different missions, as presented in (Ambrosio et al., 2006; Ambrosio et al., 2007). The support provided by this tool is fundamental for the maintenance of the satellite in orbit due to the high costs of a space mission, which can reach over US$ 300 millions, as in the case of CBERS-4 (CBERS, 2018a). For this satellite, CBERS-4, INPE has developed an operational satellite simulator named SimCBERS (Rodrigues et al., 2017a).

Although the SimCBERS project was already delivered, the developed models, which mimics the real world, may be re-used in other simulators and are a rich source to continuous improvements and studies. In this context, we proposed a study, as practical activity, for students attended the Winter Course on "Introduction to Space Technologies" [1], to perform an identification by subspace method and thus obtain more precise models. The study focused to identify the models that represents the equipment of the Electrical Power Supply Subsystem (EPSS). This subsystem was chosen due of its large number of analog parameters.

In accordance with Viberg (1994), Coelho and Santos (2004) and Souza and Trivelato (2003), identification is the act of obtaining a descrip-

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[1] The Winter Course was held in July 2017, at INPE. (CI, 2017)

tion of a system, generally mathematical modeling, with a particular objective, based in measures of its variables (inputs and outputs). In this work, the variables for the identification of the models are the flight data of CBERS-4, also known as telemetry. Telemetries are the measurements made on the satellite equipment, which can be analog (current, voltage, temperature) or digital (on/off, main/ redundant). The purpose of these measurements is to provide information about the satellite health during its operation (Fortescue et al., 2004a).

Here, the models were identified in order to evaluate the replacement of the current subsystem models, initially implemented in the operational simulator.

Historically, the operational simulators used and developed at INPE do not provide facilities for updating the models during the satellite operations. In this way, the model identification technique can be an alternative to provide reliable simulation results and progressive upgrades of the models, to the satellite operating team.

The simulator projects for the operational phase presented several types of models in a simulation environment, for example, dynamic models, which are described in mathematical equations (Kang et al., 1995), block diagram (Bodin et al., 2012), behavior models, as rule-based models (Tominaga and Ferreira, 2012; Tominaga et al., 2012) and hybrid models which take in account virtual and hardware models (Kuijpers et al., 2008). In such references, there are no reports of updating the models, already implemented, applying identification techniques using real flight data. More recently, the use of genetic algorithms to obtain updated models, guaranteeing a high degree of fidelity of the simulations, was presented in (Tominaga et al., 2016; Tominaga et al., 2017).

In our paper we applied an identification technique in order to obtain the dynamic models of equipment of EPSS, that can replace the models implemented in the SimCBERS operational satellite simulator. In addition, we verified the application of two control techniques in this type of simulator in order to reduce the error generated during the simulation.

The main contributions of this paper are:

- To use of identification and control techniques to obtain a reliable equipment model of a subsystem for an operational satellite simulator.
- To compare of the results of the current model of the SimCBERS against the results obtained from the model obtained through identification technique.
- To evaluate the performance of the identified model.

The paper is organized as follows: section 2 presents an overview of the CBERS Program, the three equipment of the EPSS to be identified and the SimCBERS simulator, including a comparison between SimCBERS current results and the real telemetries received from the CBERS-4 satellite; section 3 presents the methodology adopted in this paper, which includes the data sample collection, identification and control technique; and finally, section 4 presents the comparisons between the identified model and the corresponding telemetries produced by real satellite.

2 Problem Definition

The China-Brazil Earth Resources Satellite (CBERS) Program is a mutual technological effort between Brazil and China in order to develop, assemble and operate Earth observation satellites. Their images are used for several purposes, such as controlling deforestation and burning in the Amazon Forest, monitoring water resources, agriculture, etc. (CBERS, 2018a; CBERS, 2018b). CBERS-4, currently in operation, has 15 subsystems (CBERS, 2018c; INPE, 2018) and these subsystems are represented in the SimCBERS simulator through 408 inputs (telecommand) and 629 outputs (telemetry).

In particular, the Electrical Power Supply Subsystem of the Satellite (EPSS) is in charge of delivering, storing, distributing and controlling the electrical energy of the satellite loads (Wertz and Larson, 1999; Patel, 2004; Fortescue et al., 2004a).

According to (Magalhães, 2005; Magalhães, 2012; Torres, 2014; Magalhães, 2014), the CBERS-4 Satellite 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), as shown in the Figure 1.

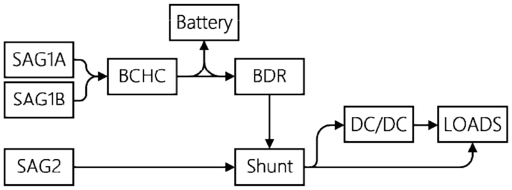

Figure 1: EPSS Diagram Block.

Torres (2014) describes the equipment of EPSS, as follows:

- 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.

- 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.

- The batteries store the energy from the solar arrays during the periods that the satellite is illuminated by the Sun, and during the eclipse, they provide the energy for the satellite loads. During the sunlight period, if the energy provided by SAG$_2$ is not enough to supply the satellite loads, the batteries can also complement this demand.

- 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 have active control, which means that they are feedbacked depending on the temperature and battery voltage. The BHCs, also having one for each battery, are responsible for the heat control. The control receives feedback by the temperature signal and actuates in the heaters located above the batteries.

- The DC/DC converters are in charge of converting the main bus voltage to smaller regulated voltages, when the loads of the satellite are not connected to the main bus (28 V).

2.1 SimCBERS - CBERS Operational Satellite Simulator

The SimCBERS Simulator is a software tool structured as illustrated in Figure 2, comprising a core or infrastructure, some facilities and a set of different models that mimicking the satellite subsystems. The SimCBERS is configured to simulate all the 15 subsystems of CBERS-4, perform the orbit propagation, the space environmental conditions and the ground stations.

As a starting point, some simulations were performed in SimCBERS and the results compared against the real satellite telemetries. These telemetries were processed by the Satellite Control System (SATCS), a software processes the telemetries received directly from the CBERS-4 satellite (Cardoso et al., 2010).

This paper presents the results of only three parameters, chosen by the degree of importance for the satellite health. The chosen parameters were: output current of the BDR (I_{BDROUT}) and voltage of one of the batteries (V_{BAT1}).

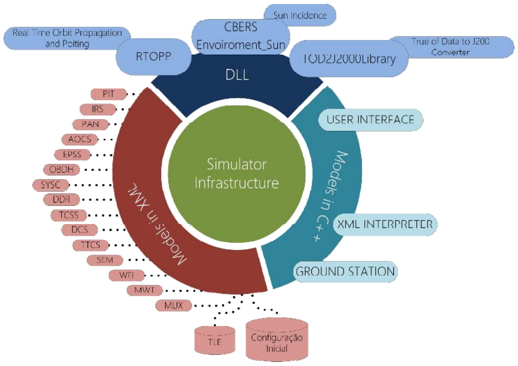

Figure 2: SimCBERS Overview.

Figure 3 illustrates the I_{BDROUT}, as produced by SimCBERS and as the real telemetry. The simulated values presented an error of 16.4%. Figure 3 also presents the V_{BAT1} values, whose error was 3.3%. The errors presented here were calculated using Equation 3.

The results produced by the SimCBERS were approved by the satellite specialists (Rodrigues et al., 2017b).

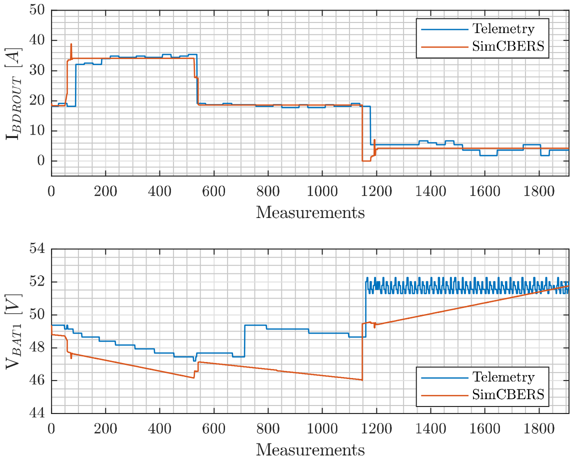

Figure 3: Comparison between real telemetry values and simulated values of the I_{BDROUT} and V_{BAT1} parameters.

As illustrated above, there was still opportunity to obtain even better simulation results, taking into account the commitment of simplicity and fidelity described by (Souza and Trivelato, 2003). In order to reduce the telemetry errors and obtain a more accurate model, the methodology used in this work is presented in the next section.

3 Methodology

One of the challenges was to execute the activities into the brief disposed time. Therefore, we restricted the identification of the space state model to 3 piece of equipment: the battery, the BDR, due to errors presented in the previous section, and the MEA (component of SHUNT), because, currently in SimCBERS, this parameter is not simulated. Moreover, we divided the activity into steps, as follows:

1. Data sample collection: the samples of real telemetries were collected using SATCS.

2. Model Identification: the equipment models were provided by `n4sid` function, implemented in MATLAB. The input of this function is from the data collected.

3. Control: in order to reduce the error between the identified model and the real CBERS telemetry, it was applied a control law.

4. Results comparison: the results of the identified and controlled models were compared with the real telemetry values.

3.1 Data Sample Collection

The data used as sampling to make the identification was collected using the SATCS software. The data is an analog telemetry, consisting of EPSS electrical currents and voltages from the CBERS-4 satellite. The telemetries are usually sent to ground stations, and from them to the Satellite Control Center, in order to allow the operation team to analyze the satellite status and health.

In this context, it is convenient to separate the telemetries in two categories: inputs and outputs. Then, it is possible to make the identification. In this work, the inputs telemetries were treated as all the inputs that affect the equipment behavior. Thus, the output telemetries were the results that the system presented, given an input.

For the BDR identification, the input currents, I_{BDRIN1} and I_{BDRIN2}, and the output current, I_{BDROUT}, were used.

In the case of battery identification, there were used four 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}). The output of this identification was the battery voltage (V_{BAT1}). Regarding the battery, the bus voltage is not a direct input. However, it was empirically demonstrated to be extremely important for its identification model, since the results of the identified model presented less errors when compared with the real telemetry.

Finally, for the MEA identification, the input parameters were: the BDR output current (I_{BDROUT}), the solar array current (I_{SG2}), the bus current (I_{BUS}) and the bus voltage (V_{BUS}). As the output of the system, the MEA voltage (V_{MEA}) was considered.

3.2 Model Identification

Due to the complexity of the equipment of the EPSS, the identification carried out was black-box. In a black-box identification only the inputs and outputs are known. (Fortescue et al., 2004b)

We employed the identification method, known as Numerical Algorithms for Subspace State Space System Identification (N4SID), proposed by (Overschee and Moor, 1994).

To make this black-box identification it is necessary to gather input and output data from the studied system, as seen in the previous section, and then apply the `n4sid` numerical method in MATLAB. The program implemented in MATLAB provides the matrices A, B, C and D as shown in the following generic system, Equation (1) and (2), where "$u(t)$" is the input array, "$x(t)$" is the state-vector and "$y(t)$" is the output array. The order of the system, in all cases, was suggested by MATLAB.

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (1)$$

$$y(t) = Cx(t) + Du(t) \quad (2)$$

The steps of identification and validation of the model, shown in Figure 4, were:

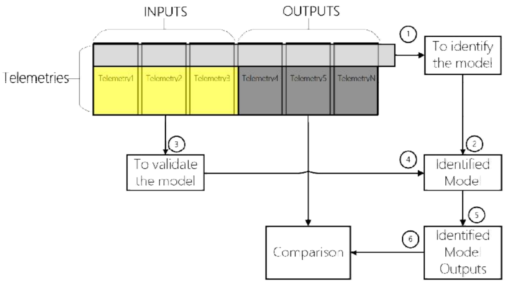

Figure 4: Identification Steps.

- The first step for the identification was to process around 15000 real telemetries from almost 150000, available of each input and output described before, using MATLAB. The idea was to find the space-state, using `n4sid`, which best describes the equipment behavior. Separating the inputs and outputs, it is possible to obtain the matrices (A, B, C and D). In Figure 4, this step is represented by circles 1 and 2.

- Then, the equipment was simulated, in Simulink, as observed in Figure 5, using as input the telemetries not used in the identification step. In this scenario, the inputs are the real telemetry, and the outputs generated were the results of the identified model ($\hat{y}$). In Figure 4, this step is represented by circles 3 to 5.

- To validate the identified model, the output obtained from the simulation is compared with the real telemetry values obtained from CBERS-4. In Figure 4, this step is represented by circle 6.

Figure 5: State-Space simulation to get the results from identified models.

The Mean Relative Squared Error (MRSE) (Borjas and Garcia, 2004) was calculated to verify if the results are as expected with the expression:

$$e(\%) = \frac{1}{no}\sum_{q=1}^{no}\left[\sqrt{\frac{\sum_{t=1}^{val}(y_q(t)-\hat{y}_q(t)^2)}{\sum_{t=1}^{val} y_q(t)^2}}\right]100 \tag{3}$$

where y_q(t) is the q-th real output data, $\hat{y}_q$(t) is the q-th simulated output data, no is the total number of outputs and val is the amount of data used to validate the model. The MRSE (e(%)) demonstrates the ability to adjust the model against the real measurements of the system, which means that the closer the $MRSE$ is to 0, the better the identified model is (MACHADO et al., 2012).

3.3 Pole Placement Control

In order to improve the performance of the system, we implemented a control block to reduce the regime error. Two simple control laws were applied, due to their implementation simplicity. As the SimCBERS performs 15 different models, considering only the satellite, from the point of view of computational cost, to add very complex controllers could demand too much processing time to the SimCBERS simulator, which can make the simulation infeasible, according to the SimCBERS requirements (Ambrosio and Branco, 2017).

At first, we used the pole placement control. To accomplish this, a feedback block, K, was included in the diagram as illustrated in the Figure 6. Moreover, the poles were removed from their initial positions. In order to implement it, the eigenvalues of the system using MATLAB, were founded, and then they were multiplied by a value corresponding to the desired distance from the poles. The gain matrix K was computed by function `place`. Several distances were tested until finding out the one that resulted the smaller error in the output.

To decrease even more the error, it was implemented a pole placement control with integral feedback. In this method, the outputs $y(t)$ are compared with a reference value $y^*(t)$. The difference between them $e(t)$ goes to an integrator, and then the system was feedbacked, as shown in Figure 7. The order of the system increases, so it was added two other poles and then, using the same procedure as used in pole placement control, the feedback gain matrix was calculated by the software.

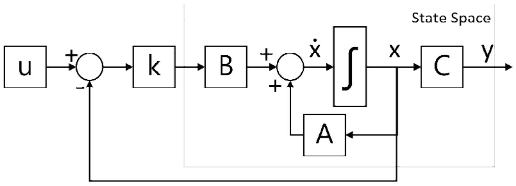

Figure 6: Pole Placement Diagram.

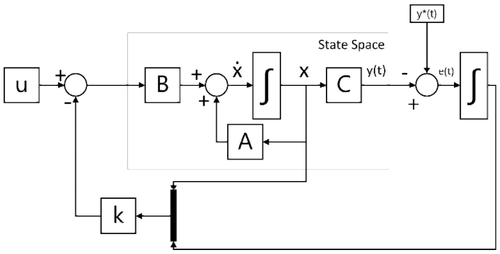

Figure 7: Pole Placement with Integral Feedback Simulink Diagram.

4 Results and Analysis

The results will be considered satisfactory when they were smaller than the results produced by SimCBERS, as shown in Figure 3, section 2.1.

4.1 BDR

The I$_{BDROUT}$ obtained from identified model of BDR, as shown in Figure 8, demonstrated, by visual inspection, that this model adheres to the real telemetry behavior. The calculated error (MRSE) indicated difference in order to 11.7547%, between the real and the identified.

Then, in an effort to reduce the error, we used the pole placement method. Several distances between the poles and the imaginary axes were tried until finding the one that resulted in lesser error. At the end of this process, a slightly smaller error than the SimCBERS result was found, about 6.94%.

Although the previous error was smaller, an integral feedback was implemented. Then, resulting in an 0.0462% error. It also decreased the steady state error and the stabilization time.

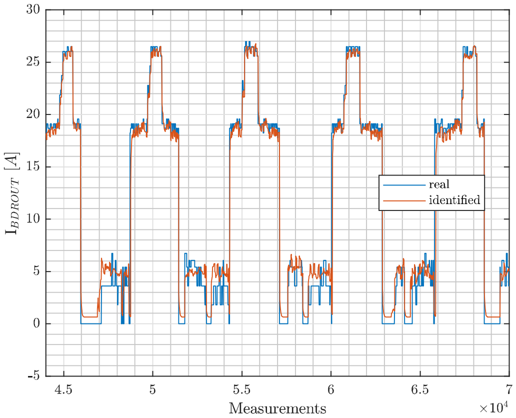

Figure 8: Comparison of the results of the identified model and actual telemetry of the BDR output current.

4.2 Battery

In the battery identification by the subspace method, observed in Figure 9, the $e(\%)$, between the V_{BAT1} telemetry and the simulated, 2.25%. The controllers did not show any improvement over the error.

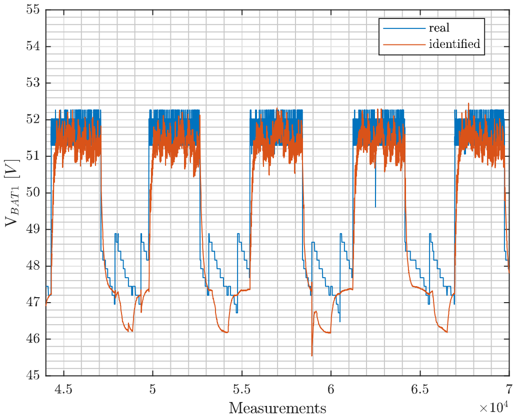

Figure 9: Comparison of the results of the identified model and actual telemetry of the Battery Voltage.

4.3 MEA

Although the MEA voltage is a design requirement (Torres et al., 2010), it is not implemented in the simulator, so obtaining this model through the model identification suggests even more fidelity to the SimCBERS simulator.

Similarly to the others identifications, the initial error was of 13.48%. The comparison can be observed in Figure 10. With the pole placement implementation, the error was decreased to 2.64%. Then, the integral feedback was implemented, the error decreased greatly, indicating that the integral action worked quite well in this case. With the integral feedback control the error (e%) was $5.8390e^{-13}$.

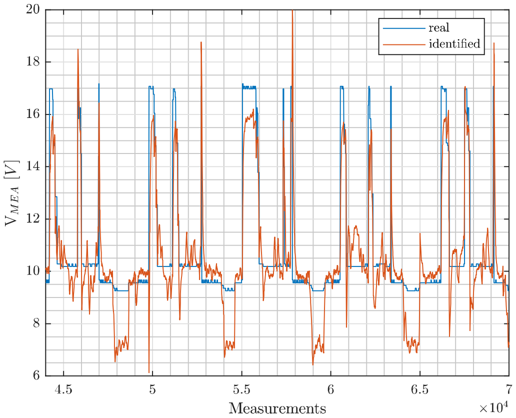

Figure 10: Comparison of the results of the identified model and actual telemetry of the MEA voltage.

5 Conclusion

In the work developed with the students that attended the Winter Course on "Introduction to Space Technologies" at INPE in 2017 and using a real and huge Project of the CBERS-4 Operational Satellite Simulator we provided a practical application of simulation model improvement. We adopted the identification technique to model satellite equipment and it showed to be an efficient method, in particular to the satellite BDR, MEA, BAT1 equipment, since the error analysis presented satisfactory results for all models identified.

The control methods adopted had different results for each of the models. First, the pole placement and the integral feedback control were good for BDR output current and MEA voltage, because it was possible to reduce the error of the model. In situations in which the satellite needs to be stressed to achieve a particular goal, perform simulations with reliable models can be more valuable.

Conversely, the model of the battery did not accept any actuation of the controller. One of the reasons that may have contributed to this, was the empirical way to define the amount of data used in the identification and also the distance of the poles. As a continuity of the work, other methods of identification and other types of controllers could be studied to be applied in the simulator to obtain better results.

In addition, we conclude that it is possible to use this method to improve the subsystem models results, early in the satellite development, for instance, during the Assembly, Integration and Test (AIT) phase, what would lead to a gain in the fidelity of the operational simulator for the INPE satellites in development,, such as CBERS-4A, Amazônia-1 and Equars.

Other verification and control techniques can be tested in future work.

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