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AN INTEGRATED SPACE SYSTEM DESIGN TOOL KIT FOR THE ITA SPACE CENTER'S PROJECTS

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Abstract. *During the conceptual phase of a space mission, when the requirements and restrictions of the project are still being explored and defined, the design team's focus is mainly on carrying out trade studies. Therefore, in this phase, it is more important to perform extensive and wide research through the design space, instead of conducting deeper analysis. However, the design of space systems is a complex and multidisciplinary task that includes several technical aspects of the engineering field. A trade analysis consists of evaluating alternative design options during the conceptual study phase taking into account. Such analysis, in general, is executed by a team of specialists in different knowledge fields working together. Going in this direction, the recently founded ITA Space Center has also used a concurrent engineering process for developing its projects of small satellites. Therefore, this work aims to show a computational tool kit for assisting the conceptual design of space systems in an integrated and systematic way. The proposed method has been built in a dynamic script that combines code, input and output data, formatted text, and images in an executable framework increasing and expanding the computational capacity. This work aims to describe the conceptual operation of the proposed model, considering, in this first phase of the project, the main disciplines of a satellite design: orbit, propulsion, attitude control, and power.*

Keywords: *Space systems design, Spacecraft, Concurrent Engineering, Design process*

1. INTRODUCTION

When one intends to carry out the project of a space mission, it is essential to have computational integrated methods to generate possible configurations of orbits and, consequently, feasible solutions of subsystems' conceptual design. Satellites have interdependent subsystems, which imposes that during the different design phases, it is necessary to explore the design space and to iterate the results in order to reach the best compromise configuration that meets the mission requirements (Wertz *et al.*, 2011).

The design of aerospace systems demands the application of computational tools that allow quick visualization and analysis of the results obtained during the iteration loops of the concept project phase. Over the last decades, several computational models have been developed and applied for this purpose. For example, the Virtual Satellite Software

was created with the purpose of replacing the various electronic spreadsheets of the German Aerospace Center (DLR) during the development of the preliminary phases of a project (Deshmukh, 2013). The T-SMAD (Tools for Space Mission Analysis and Design) uses Matlab© -based software to support engineers during the initial stages of a mission design (Radice, 2014). In the national context, a multidisciplinary tool for the concept of operation simulation, called FOrPlan, has been developed by the Space Missions Integrated Design Center (CPRIME) of the Brazilian National Institute for Space Research (INPE). FOrPlan has the capacity of performing several functional simulations of the satellite and ground segments, providing to the INPE's concurrent engineering group, CPRIME, a reliable verification tool for the space mission development (Chagas *et al.*, 2019).

The efficiency of the conceptual design phase of a new satellite can be highly impacted by how some engineering tools are used, such that they can determine the main parameters and drivers of a space mission. In this context, this work presents a tool developed in Matlab©, by using the Live Editor interface. Called SSDTK – Space Systems Design Tool Kit, it integrates, initially, the main elements of a satellite design: orbit, attitude determination and control subsystem (ADCS), propulsion, and power. As shown in Fig. 1, it allows better interaction with the user by enabling them to carry out simulations and viewing the results in an integrated and systematic manner.
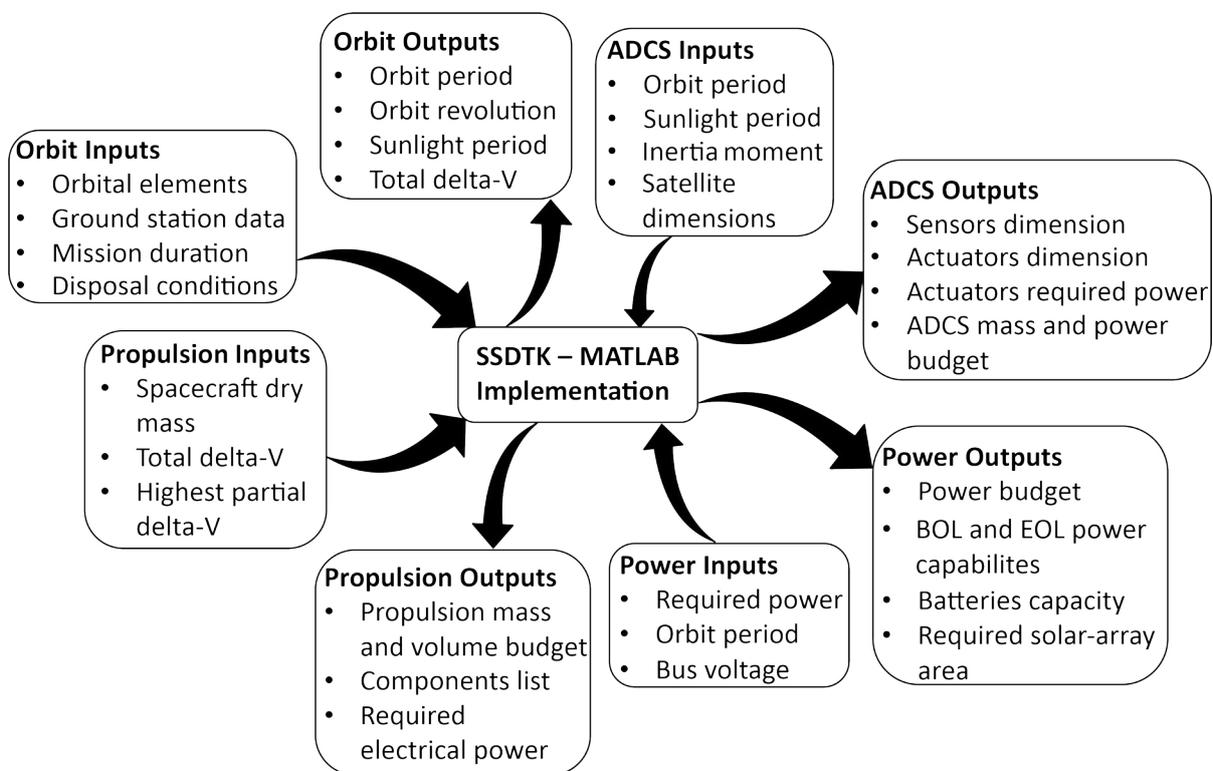

Figure 1. Main parameters of the SSDTK implementation.

This project considers two major phases. The first one, described in this paper, includes the following tasks: codification of the parametric equations available in Wertz *et al.* (2011); joint of the input and output data at the same computational environment; and development of an intuitive, user-friendly, and executable framework to increase and expand the computational capacity. It is worth mentioning that the ranking and selection, among the competing alternatives, of the best compromise solution is out of the scope of this work. Such procedure, as well as the inclusion of a Multidisciplinary Design Optimization (MDO) technique, is highly desirable and will be taking into account in the continuity of this project (phase 2).

For the validation of the proposed method, we have considered the parameters of the Amazonia-1 mission as a case study. The Amazonia-1 is an Earth Observation satellite, illustrated in Fig. 2, designed, tested, and operated by the Brazilian National Institute of Space Research (INPE). The main objective of that mission is to monitor the deforestation that occurs in the Amazon rainforest region in Brazil (INPE, 2021).

The SSDTK has been created and implemented in the Aerospace Systems Simulation Laboratory (LSSA) of the ITA Space Center (CEI, in Portuguese) to support the conceptual design of small satellites developed by the Brazilian Air Force (FAB). This paper is organized as follows. The methodology is addressed in Section 2, comprising the definitions of the analyzed subsystems. Section 3 presents the results calculated for each subsystem using the SSDTK interface, applying the initial data from the Amazonia-1 satellite mission. The conclusions are discussed in Section 4.
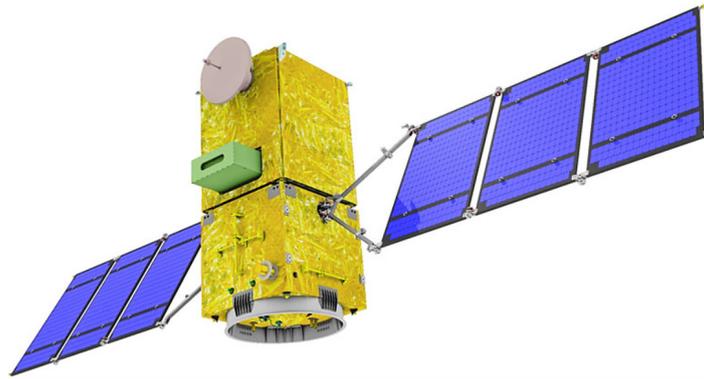
Figure 2. Illustration of the deployed Amazonia-1 spacecraft (Source: INPE, 2021)

2. METHODOLOGY

Currently, the SMAD (Space Mission Analysis and Design) process is widely used in the analysis and design of space missions. According to Wertz *et al.* (2011), this process consists of four steps: (1) definition of the objectives and constraints of the space mission; (2) definition of concepts for its application; (3) evaluation of these concepts; and (4) determination of the requirements for the operation of the system and subsystems.

The mission requirements are firstly defined, followed by the orbit design, and latterly we have the design and dimensioning of the subsystems: Propulsion, Attitude Determination and Control System (ADCS), and Electrical Power System (EPS). Fig. 3 shows some capacities of the proposed integrated environment, SSDTK, developed in Matlab©, which includes: table of contents (with fast access through hyperlinks); several plots showing the behavior of the main variables; fundamental theoretic concepts behind the algorithm; user-friendly input parameters field; among others resources.
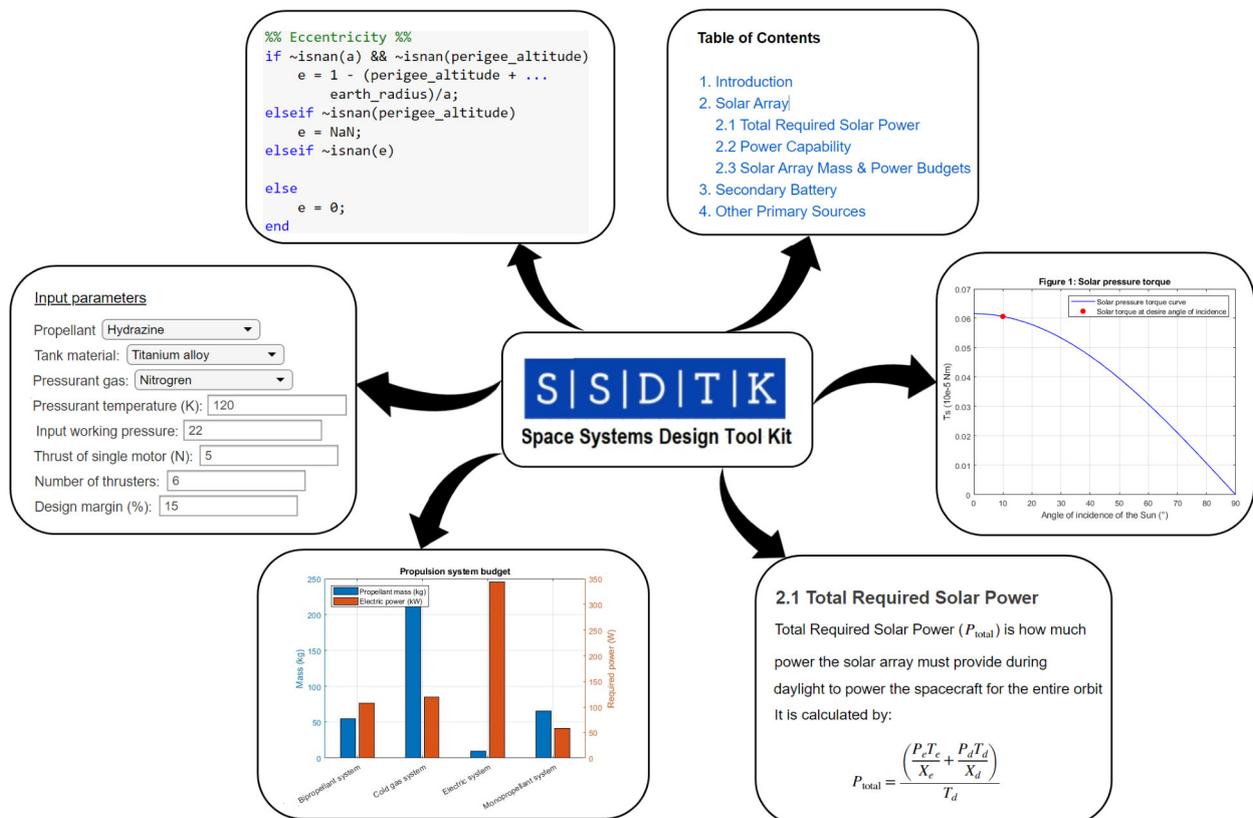

Figure 3. The SSDTK integrated environment in Matlab©.

The following subsections aim to describe, with more details, the process of design of each considered space system's element. All the mathematical modeling used in this process are mainly based on Wertz *et al.* (2011) and Ley *et al.* (2009); London (1996).

2.1 Orbit design

In order to establish, for example, which orbit is the best option for a given mission, how a satellite will move in space, or which portion of Earth can be seen from a satellite camera, the orbit design process will define the space mission lifetime, cost, environment, viewing geometry, and payload performance based on the classical orbital elements: inclination, eccentricity, semi-major axis, the longitude of the ascending node, the argument of the periapsis, and true anomaly. The orbital elements are fundamental parameters to define the orbit, such as its shape, size, the orientation of the orbital plane, and position of the satellite (Carrara *et al.*, 2012).

The orbit selection and design process is summarized and shown in Fig. 4 (Wertz *et al.*, 2011). First, the space mission is divided into segments in order to classify it by its overall functions and identify the basic orbit type. Then, requirements are defined for each segment, including orbital limits, altitude for observations, or constraints for any of the orbit parameters. Next, the performance of all orbits is evaluated regarding their coverage and impact on the mission. After that, the launch cost, disposal options, ΔV budget, and orbital cost function are estimated and evaluated. Finally, the mission requirements used to define the orbit, the reasons for selecting it, and the numerical values of the selected orbit parameters are documented, and the nominal solution can be reevaluated if the mission conditions change.
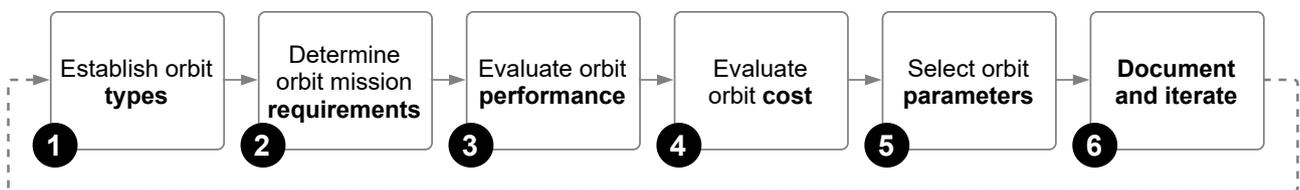

Figure 4. Orbit design workflow.

2.2 Propulsion subsystem

For the propulsion subsystem, it is defined the propellant mass and dimensioning of the tank (mass and volume), considering the total ΔV necessary for the orbital maneuvers, and the dry mass of the satellite as input data. The main functions of a satellite propulsive subsystem are orbital transfer, orbit maintenance, discard and reentry operations, and attitude control maneuvers, being differentiated by the energy source (propellant) and the way in which the thrust is generated (Ley *et al.*, 2009; London, 1996).

While cold gas-based propulsion systems are rarely used, they are quite simple and cheap solutions. The solid propellant-based systems are the most common for insertion into orbit. The liquid monopropellant systems are usually used for the maintenance of orbit and attitude control. Despite showing high performance while conducting all these activities, liquid bipropellant-based systems imply a significant increase in project complexity. The process for selecting and sizing propulsion subsystem components is illustrated in Fig. 5 (Wertz *et al.*, 2011).
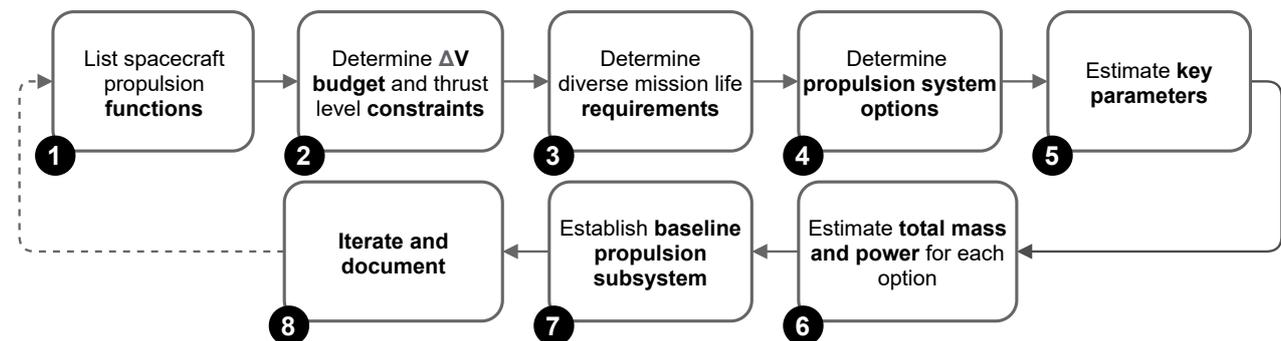

Figure 5. Propulsion subsystem workflow.

2.3 Attitude determination and control subsystem (ADCS)

The proper design of the ADCS is highly important in every space mission since its wrong dimensioning can lead to excess fuel expenditure and, in the worst case, loss of the mission (Wayer *et al.*, 2013). It basically consists of the process of orienting the spacecraft to point in the desired direction. Given the design requirements, control modes are defined, which consist mainly of the phase of orbit acquisition, orbital insertion, normal on-station operation, and slew maneuver (Wertz *et al.*, 2011). Figure 6 shows the main steps for the ADCS design. They must be iterated throughout the project to achieve better results.

The SSDTK's ADCS model aims to organize the requisitions for each part of the mission, quantify disturbances effects on the spacecraft, size and select both actuators and sensors to supply mission needs. The selected hardware components are present in a database included inside the program folder as a Matlab© file, examples of these devices are suns and stars sensors, magnetometers, gyros, GPS, reaction wheels, magnetic torquers, and control moment gyros (CMG).
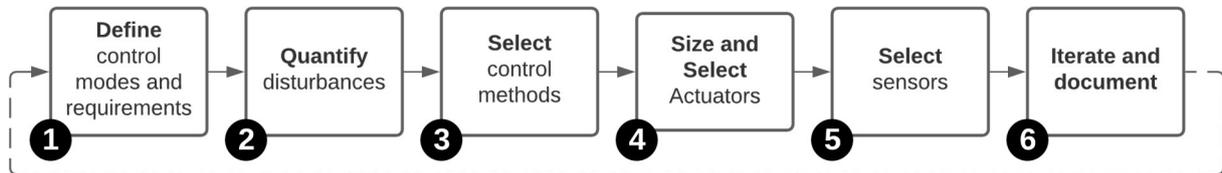

Figure 6. ADCS subsystem workflow.

2.4 Electrical power subsystem

The EPS has the main function of generating, storing, regulating and distributing electrical energy to the components and other subsystems of the satellite. This is a critical subsystem because all components need electric power to function properly. For a preliminary and initial approach to the power system design, as shown in Fig. 7, the following steps will be taken chronologically after identifying the requirements: select and size the energy source and the storage system, design the energy distribution, control and regulation, and, finally, estimate the mass, peak power, and average power requirements (Wertz *et al.*, 2011).

Most space missions aim to place satellites around the Earth. In this case, photovoltaic cells (or solar cells) are chosen as a power source because the total power required during the mission is less than 15 kW and the technology used is reliable and well-known. Moreover, when photovoltaics cells are used, an energy storage technology is needed, for instance, batteries are usually employed (Wertz *et al.*, 2011). Therefore, the SSDTK focuses more on solar arrays and secondary batteries (rechargeable) than the others power sources and energy storage.
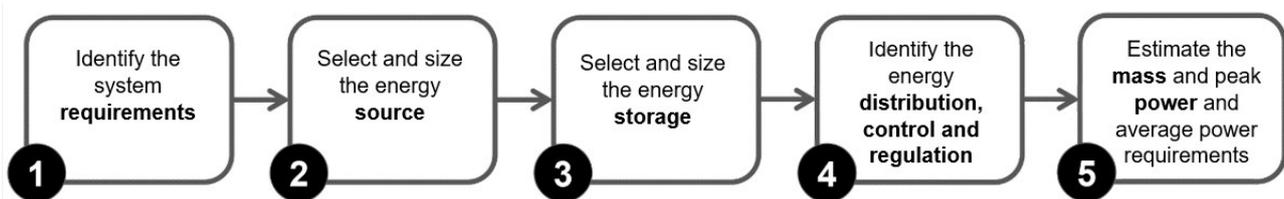

Figure 7. EPS subsystem workflow.

2.5 SSDTK's database

A database for the propulsion subsystem design has been developed in the SSDTK Matlab© environment. It is composed of several models of tanks and commercial thrusters, whose technical data vary according to the manufacturer's datasheets. Once the main design parameters of the propulsion subsystem have been calculated, one can check the "Display tanks/thrusters database" box (see Fig. 8) for the tanks and thrusters database to pop up on the screen. The tank should be selected according to the required propellant mass and volume computed in the earlier steps. Likewise, a thruster model has to be selected in order to satisfy the attitude and orbital maneuver requirements. There are, to date, 155 tank models and 110 propeller models available in the database, which should be updated frequently.

Another database has been implemented in the SSDTK concerning the ADCS's devices. It includes values of mass, dimension, and technical data of both actuators and sensors. Up to now, the ADCS database comprises the following models: 45 reaction wheels, 4 control momentum gyros (CMG), 30 magnetic torquers, 24 sun sensors, 6 earth sensors, 16 magnetometers, 23 stars sensors, 27 gyros, and 12 GPS models, such that they can be selected based on mission requirements and environments disturbances. New devices and technologies are constantly being added to keep the database updated.

3. RESULTS

This section discusses the design of a satellite with characteristics similar to the Amazonia-1 satellite, covering the four subsystems previously discussed. Input data, based on Amazonia-1, and output data, obtained through the integrated
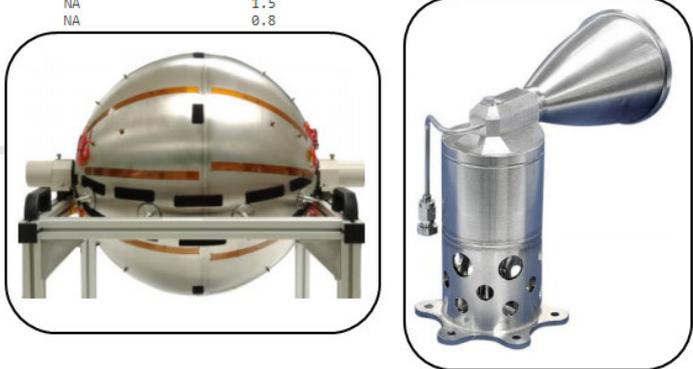
Figure 8. Overview of the SSDTK'S tanks and thrusters database.

conceptual design tool (SSDTK) by the SMAD method, are presented here. Furthermore, the results are compared and discussed with some data from the Amazonia-1 satellite.

3.1 Input parameters of the SSDTK

The main input parameters used by the subsystems are presented in Table 1. Such values can be found in eoPortal Directory (2021) and, also, obtained directly with some specialists of the mission at INPE.

Table 1. List of the main input parameters of SSDTK for Amazonia-1 mission evaluation.

Input parameters	Value	Unit
Circular orbit altitude	752	km
Inclination	98.4	°
Eccentricity	0	-
Mission duration	4	years
Solar activity	Minimum	-
Start date	02/28/2021	-
Orbital period	99.86	min
Inertia moment on the X axis[1]	320	kg.m²
Inertia moment on the Y axis[1]	80	kg.m²
Inertia moment on the Z axis[1]	320	kg.m²
Sunlight surface area[1]	2.5	m²
Ram area[1]	2.5	m²
Daylight required power	640	W
Eclipse required power	390	W
Maximum eclipse time	35.2	min
Worst-case Sun incidence angle	64.52	°
Spacecraft dry mass	500	kg
Total ΔV	80.82	m/s

[1] Estimated values based on the vehicle's geometry

3.2 Output parameters of SSDTK

After the computation performed by the SSDTK software, the main output values calculated by the subsystems are presented in Table 2. A brief discussion about the results of each subsystem is provided below.

Table 2. List of the main output parameters of SSDTK for the designed satellite.

	Output parameters	Value	Unit
Orbit design	Orbital period	99.86	min
	Orbital revolution	14.42	revs/day
	Total specific energy	-27.95	km²/s²
	Mean angular motion	0.06	°/s
	Satellite velocity	7.48	m/s
	Maximum eclipse time	35.2	min
	Minimum sunlight period	64.66	min
	Worst-case Sun incidence angle	64.52	°
	Total ΔV	80.82	m/s
Propulsion	Type of propulsion	Monopropellant	-
	Fuel propellant	Hydrazine	-
	Propulsion system total mass	42.6	kg
	Propellant mass	24.93	kg
ADCS	ADCS total mass	53.2	kg
	Sensors required power	56.2	W
	Actuators required power	278.4	W
	Total ADCS required power	334.6	W
EPS	Total required solar power	1154	W
	Solar array area	8.22	m²
	Solar array mass	46.16	kg
	Battery capacity	1167.4	W.h
	Total EPS mass	105.51	kg

3.2.1 SSDTK's result: Orbit design

As previously presented, the case study is based on the Amazonia-1 mission. Because of that, similar orbital input parameters are used (Table 1). Among its characteristics, a Sun-synchronous orbit stands out due to a 98.4° inclination. From the classical orbital elements, it is possible to obtain the orbit dynamics and estimate the cost for its maintenance and maneuvering (ΔV budget). From the start date, the solar incidence angle's profile is obtained, in which the worst-case Sun incidence angle is assumed. The total ΔV is the sum of the parking and operational orbits burns (15.93 m/s), altitude maintenance burn (0.07 m/s), and spacecraft disposal burn (64.82 m/s).

A direct comparison can be made between the orbital parameters results obtained from the SSDTK software for the designed satellite (Table 2) and a few reference values for the Amazonia-1 satellite, taken from INPE and from the Ref. eoPortal Directory (2021). As expected, due to the nature of the orbit, the exact same values for the orbital period and revolution, as well as the total specific energy, mean angular motion, and maximum eclipse time for both satellites are obtained. There is not enough information about the ΔV budget of Amazonia-1, nevertheless, it is believed that, for a first iteration, the obtained total ΔV result is reasonable.

3.2.2 SSDTK's result: Propulsion

The propulsion subsystem design process starts by assuming a monopropellant-based system since it is the system used in Amazonia-1. Once the main inputs for this calculation are informed (total ΔV and spacecraft dry mass), some design parameters must also be included in order to achieve better results. The INPE (2014) portal informs these parameters, such as the number of thrusters, fuel propellant, pressurant gas, and the input working pressure. Zandonadi *et al.* (2013) also brings some important data about the Amazonia-1 propulsion subsystem that will be used as comparison parameters for the results obtained by the SSDTK model.

The SMAD calculation process yielded results of 24.93 kg of loaded propellant (corresponding to 24.68 l) and an internal tank volume of approximately 32.9 l. Then, a database of commercial tanks is searched for any model that satisfies this requirement of internal volume and propellant mass, considering the monopropellent system. Therefore, the tank selected during this first iteration is the spherical PEPT-420 model from the manufacturer RAFAEL, which has an internal volume of up to 37.3 l and a total mass of 3.6 kg (RAFAEL, 2014).

Regarding thrusters, the model selected is the same used in the Amazonia-1 satellite, the FM-5N model developed by the Fibraforte manufacturer, which has a nominal thrust up to 5 N and weighs approximately 0.32 kg. Considering the total thrust requirement of 43.85 N obtained during the calculations, at least 9 thrusters are required.

It is known from the work of Zandonadi *et al.* (2013) that the tank used in Amazonia-1 has a total internal volume of

60 l, with a capacity for 45 l of loaded propellant. Furthermore, it is known that, in all, 6 thrusters are used in Amazonia-1. This difference in results is considered, at this first moment, to be reasonable and optimistic, considering that several parameters were only estimated based on historical data, in the absence of realistic data. In addition, the total ΔV, the main input parameter for the propulsion subsystem calculations which significantly affects the results, was calculated, at the orbit design stage, from other estimates made temporarily, not being a value until then fully validated. New iterations, added with the input of real data from the model satellite, will be necessary in order to obtain results closer to the reality of the Amazonia-1.

3.2.3 SSDTK's result: EPS

The main input parameters in EPS are mission duration, orbital period, maximum eclipse time, worst-case Sun incidence angle, and required power during daylight and eclipse (values are shown in Table 1). Orbital period, maximum eclipse time, and worst-case Sun incidence angle are taken from the orbit design stage (previews section); mission duration, required power during daylight and eclipse, were based on Amazonia-1 mission. The daylight power required is the sum of the receiver (10 W), transmitter (30 W), payload (250 W), and platform multi-mission (350 W) totaling 640 W. Assuming that the payload works only during daylight, then the power required during eclipse is 390 W. These power values are based on INPE's expert information.

With the inputs mentioned previously, combined with values taken from the Reference (Wertz *et al.*, 2011), it is possible to estimate the characteristics of the solar arrays and the secondary batteries (see Table 2). The satellite designed here has a solar array area with 8.22 m², comparing to the Amazonia-1 satellite which has two solar arrays and a total area of about 6 m². Considering that the present work aims to design a satellite similar to Amazonia-1, this first iteration for the solar array area is quite reasonable.

3.2.4 SSDTK's result: ADCS

The first step of the attitude design process is the definition of the guidance requirements and control methods based on mission goals. This generally begins with a brief description of these requirements and, next, a selection of the type of control method is made. The procedure of selecting control methods must consider the effects of orbit insertion, payload pointing, slewing, and accuracy requirements that will influence the class of sensors and the number and type of actuators.

After defining the control modes, the next step is to quantify disturbances acting on the spacecraft. The equations used to model the major disturbances are presented in Wertz *et al.* (2011). The inputs considered in this preliminary analysis are provided by others SSDTK subsystems and structural estimates based on the satellite dimensions (INPE, 2021), in addition to comparisons with similar missions (Wertz *et al.*, 2011), are listed in Table 1. The results of these disturbances are presented in Fig. 9 (left).

6.5 Summary of Disturbances

Table 12: Summary of disturbances

	Values	Units
Solar Torque	5.4718e-06	Nm
Atmospheric Torque	7.3657e-06	Nm
Magnetic Torque	3.1461e-05	Nm
Gravity Gradient torque	6.8948e-05	Nm
Total Disturbance torque	0.00011325	Nm
Total disturbance at 5° Pitch angle	4.4299e-05	Nm
Total disturbance at 5° Roll angle	0.00011325	Nm

Uptake

7.6 Summay of actuators desgign

Table 13: Summary of actuator design

	Values	Scale	Unit
Torque from Reaction Wheel	3509	1e-05	Nm
Momentum Storage by Reaction Wheel	8.778	1	Nms
Magnetic Torquer Dipole	250	1	Am²

Update Table

Figure 9. Summary of disturbance (left) and actuators design (right) results for Amazonia-1 satellite.

Analyzing the Amazonia-1 mission (INPE, 2021), the result of the required ΔV from SSDTK Orbit definition and the disturbance summary is presented in Fig. 9 (left). The ADCS output list of devices includes a zero momentum (3 wheels) control method with a fourth wheel added for redundancy; magnetic torquers; Stars and sun sensors; and GPS, and gyros for attitude determination. The next step is to size these actuators, evaluating the minimal performance level to meet mission requirements. These values, shown in Fig. 9 (right), will be used to select both reaction wheels and magnetic torquers available commercially.

At last, the actuators and sensors are selected based on the SSDTK database. Reaction wheels and magnetic torquers have been selected so that they can supply the calculated storage momentum and torque dipole individually. Sensors have been chosen based on the mission requirements. The Sun and star sensors were selected for attitude determination and estimating the Sun vector. GPS has been used for positioning, and the magnetometer is used to measure the Earth's magnetic field. Figure 10 show all components selected along with their characteristics of supplier, mass, and power consumption. These devices are similar in number, type, and required power to those used in Amazonia-1 satellite (INPE,

2021).

10.1 Actuators

Table 20: Actuators selected

Type	Rationale	ID	Code	Mass	PowerON	PowerIddle	PowerMean
ReactionWheels	Three axis attitude control	22	Rockwell CollinsRSI12-75/60	4.85	66	0	20
ReactionWheels	Three axis attitude control	22	Rockwell CollinsRSI12-75/60	4.85	66	0	20
ReactionWheels	Three axis attitude control	22	Rockwell CollinsRSI12-75/60	4.85	66	0	20
ReactionWheels	Three axis attitude control	22	Rockwell CollinsRSI12-75/60	4.85	66	0	20
MagneticTorquers	Reaction wheel unloading	26	ZARM Technik MT250-2	5.5	4.8	0	4.8
MagneticTorquers	Reaction wheel unloading	26	ZARM Technik MT250-2	5.5	4.8	0	4.8
MagneticTorquers	Reaction wheel unloading	26	ZARM Technik MT250-2	5.5	4.8	0	4.8

10.2 Sensors

Table 21: Sensors selected

Type	Rationale	ID	Code	Mass	PowerOn
StarSensor	Attitude Determination	4	EADS SODERN HYDRA-CMOS	3.31	10
StarSensor	Attitude Determination	4	EADS SODERN HYDRA-CMOS	3.31	10
StarSensor	Attitude Determination	4	EADS SODERN HYDRA-CMOS	3.31	10
Magnetometer	Measure the magnetic field	13	Surrey Satellite Technologies Magnetometer	0.19	0.3
Magnetometer	Measure the magnetic field	13	Surrey Satellite Technologies Magnetometer	0.19	0.3
GPS	Measure satelite posision and provide PPS	7	Surrey Satellite Technologies SGR-07	0.45	1.6
Gyro_IMU	Fiber-optic head (ICU)	1	Airbus EADS Astrium ASTRIX-120	6.5	24
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01
SunSensor	Estimate sun vector	23	SSBV CBSS	0.005	0.01

Figure 10. ADCS devices selected by the SSDTK model.

4. CONCLUSIONS

In this work, a Matlab©-based software dedicated to the preliminary concept and design of a space mission has been introduced. The SSDTK has been developed to integrate different subsystems presented in a satellite project: orbit definition, propulsion, ADCS, and electrical power system, using the Matlab© Live Editor interface. Starting from the Amazonia-1 satellite as a baseline mission, its main input parameters were used to verify if the outputs provided by the software were compatible with the real mission. After a first iteration, such values are consistent, showing that the results are close to those actually applied.

The intuitive and user-friendly SSDTK's visual allows a faster and integrated space mission analysis and supports the designers to take fast decisions at the beginning of the project. In addition, it provides greater flexibility once the parameters can be easily adjusted and viewed. The development of this type of integration tool has a deep impact on the technological progress of a space agency that uses it, since the results are generated much faster, being able to meet the established schedules and focus on the other stages of the project.

Future works within this project includes adding other satellite subsystems, as communication and on-board data handling, as well as the integration of a Multidisciplinary Design Optimization (MDO) technique for the ranking and selection of the best compromise solution.

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