SCALES – A System Level Tool for Conceptual Design of Nano- and Microsatellites

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Abstract

A satellite design tool has been developed offering systems engineers a fast way to analyze the feasibility of a particular design concept. The tool differs from available tools on the market in that it is specifically targeted at small satellites in the mass range of 1-50 kg, and with a limited development time. The tool is developed in Excel, and users interact with the tool in an intuitive manner through only one input and one output sheet. Required inputs include payload specifications, launcher characteristics, sensor & actuator types, and goal satellite mass, volume and power level. Outputs offered by the tool include mass, volume and power budgets, operating temperature envelope, attitude accuracy, propellant mass, transmit power and data rate. Algorithms, “rules-of-thumb” and estimation relationships linking the input parameters with the output parameters have been based on models found in current literature, but have been revised and redefined based on an extensive satellite database containing over 200 satellites in the mass range of 0.1 – 50 kg, developed at Delft University of Technology.

Keywords: nanosatellite, microsatellite, conceptual, design tool, scaling

1. Introduction

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Figure 1: Satellite mass sorted per payload type [1]

In the recent years space agencies and private corporations have shown an increased interest towards nano- and microsatellites. Nanosatellites are defined to have a mass between 1 and 10 kg and microsatellites between 10 and 100 kg [2]. These two classes of satellites offer a low-cost, low-risk and fast option for technology testing and scientific research. Universities also build nano- and microsatellites for supporting educational activities and outreach. The data visualized in Figure 1 are based on values extracted from an extensive database developed at Delft University of Technology (TU Delft), containing over 200 satellites in the mass range of 1 – 50 kg [1]. As the figure illustrates, these two classes of satellites offer a wide range of possible usage areas extending from amateur radio communications to advanced technology testing.

TU Delft is involved in several ongoing satellite development projects such as the Delfi-C³, Delfi-n3Xt, and FAST-D. Delfi-C³ is a three unit CubeSat of 2.2 kg and 3 W, operational in orbit since April 28th 2008. Delfi-n3Xt is another three unit CubeSat currently in the detailed design phase aiming at a launch in 2010/2011. FAST (Formation for Atmospheric Science and Technology demonstration) is a collaboration project with Tsinghua University in China and involves a set of formation flying microsatellites aimed for launch at the end of 2011. In the context of these nano- and microsatellite projects TU Delft is looking for further activities and tools to support the design process. As an educational institution one of the main goals is to increase student interest in satellite projects and improve the learning curve. Having a design tool would add much value in fulfilling these goals. Such a tool can be used for concept feasibility checks, for developing new design ideas and broadening the design space, for checking the system level results from a team of subsystem engineers and for teaching students the various steps involved in designing a satellite.

2. Other tools on the market

Before developing the tool a market investigation was conducted resulting in an overview of available design tools, their architectures and capabilities. Based on this overview, see Table 1, some general conclusions are drawn. Most design tools are either in-house or proprietary work, or commercially available but with rather high costs. Some tools focus on the geometric configuration of satellites, others on trajectory analysis and optimization, while most tools include the capability for detailed subsystem design. The detailed subsystem design is either based on the tool user selecting certain components from an implemented database, or utilizing scaling relationships for sizing the mass, volume and power consumption of the components. Among the tools implementing scaling relationships, none focused on satellites in the mass range of 1 – 50 kg. The implemented estimation relationships have been developed using statistical data of satellites of hundreds of kilograms to several tons in mass. Many of these relationships are not necessarily valid for extrapolation down to the lower mass range.
Table 1: Results of investigation into available satellite design tools on the market

<table>
<thead>
<tr>
<th>Tool:</th>
<th>Limitations:</th>
<th>Type of inputs:</th>
<th>Type of outputs:</th>
<th>Software language:</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAD [4]</td>
<td>Proprietary work.</td>
<td>Mass and power of most components, orbit details, payload requirements.</td>
<td>Pointing accuracy, temperature range, structural strength, link budget etc.</td>
<td>Windows MS Excel</td>
</tr>
<tr>
<td>Satellite Tool Kit (STK) [8]</td>
<td>Mainly focused on orbital maneuvers, not subsystem design.</td>
<td>Mission parameters.</td>
<td>Trajectory analysis, link parameters, ground station coverage etc.</td>
<td>Object-oriented programming language?</td>
</tr>
<tr>
<td>SMAD Support Software [9] [10]</td>
<td>Uses database for component sizing. No upgrades available. Source code is proprietary.</td>
<td>Magnetorquer coil cross-sectional area, offset between center-of-gravity and center-of-pressure etc., and mass and power of most components.</td>
<td>Overall satellite mass and power, link budget, pointing accuracy, disturbance torques etc.</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

When developing a design tool it is important to keep the potential future users and their expectations and requirements in mind. A user survey was conducted to map these requirements and distributed to the Delfi-n3Xt team members. The general conclusions drawn from this survey are that the users do not want to select components from a database, but rather implement the individual characteristics. This is to ensure flexibility towards various possible technology and design solutions. However, users also do not want to implement too detailed input at an early design stage. To minimize the number of required user inputs design estimation relationships are implemented for some of the satellite subsystems and components.

3. Modelling of design estimation relationships

The design of a nano- and microsatellite differs from the traditionally larger satellites. Investigating this difference is part of the research done at TU Delft. When performing conceptual design it is common use to take advantage of already made designs and scale to the requirements at hand. It has been looked into generating a new set of estimation relationships valid for satellites between 1 and 50 kg. The method of regression is used for
statistical analysis of satellite and component data. When limited knowledge is available regarding the physical relationship between the parameters modelled, a linear or power-law fit is used to find the best fit with the statistical data. MS Excel uses the least squares method for calculating the best fit. This method minimizes the sum of the squares of the offsets of the data points from the line [11]. Next to the equation of the best fit MS Excel displays the $R^2$ value, known as the coefficient of determination. The $R^2$ value indicates how well the estimated values for the trend line correspond to the actual data points. In our analysis also a Standard Error of Estimate (SEE) is provided for every regression fit by using Equation 1 [12]. In Equation 1 $y$ represents the actual data point and $f(x)$ represents the corresponding value calculated using the regression fit.

\[
SEE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - f(x_i))^2}{n-1}}
\]  

(1)

4. Estimation rules for nano- and microsatellite design

Figure 2 demonstrates the differences in the subsystem mass distribution on nanosatellites versus satellites up to several tons in mass [13]. Significant differences are seen in the payload, structure, propulsion, attitude determination & control, telemetry, tracking & command and the electric power subsystem. Larger satellites generally support heavier payloads, include much more propellant and have a larger electric power subsystem. This could be because of deployable solar panels and larger batteries.

![Figure 2: Subsystem mass distribution comparison between nanosatellites (8) and satellites of up to several tons in mass (15)](image)

Two examples of design estimation relationships developed are provided and compared with original relationships. The first example concerns a relationship for the spacecraft volume using the mass as independent variable. The second example concerns a mass estimation relationship for reaction wheels.

4.1 S/C volume estimation

From [13] an estimation relationship for spacecraft (S/C) volume can be found (see Equation 2) developed by TRW Defence and Space Systems Group. This relationship is based on an analysis of the (loaded) mass and volume of a number of S/C in the mass range...
from 135 kg to 3625 kg. Their density ranged from 20 kg/m$^3$ to 172 kg/m$^3$ with an average of 79 kg/m$^3$.

\[ V_{S/C} = 0.01 * M_{\text{loaded}} \quad [m^3] \]  
Mass range: 135 – 3625 kg  
Slope range: 0.005 – 0.05 (corresponding to a density range of 20 – 200 kg/m$^3$)

The estimation rule resulting from our study, see Equation 3, has a slope which is five times smaller than the original estimation relationship. This relationship is the result of an analysis of the loaded mass and volume of over 80 nano and microsatellites in the mass range 1-50 kg and a mass density in the range 200-1600 kg/m$^3$. Based on a linear statistical fit, see Figure 3, the relationship estimates a spacecraft density equal to 526 kg/m$^3$. The broad range of actual S/C density values partly explains the SEE value calculated for the data points fitted. Other reasons for the calculated SEE can be the differences in spacecraft configuration, development year, main payload type, orbital altitude, spacecraft lifetime, implementation of COTS (Commercial Off-The-Shelf) components, implementation of propulsion system and errors in the statistical data.

\[ V_{S/C} = 0.0019 * M_{\text{loaded}} \quad [m^3] \]  
Mass range: 1 – 50 kg  
Slope range: 0.0006 – 0.005 (corresponding to a density range of 194 – 1584 kg/m$^3$)  
SEE: 54.6 %

Figure 3 shows the original volume-mass relationship according to Equation (2) plotted against the linear regression fit developed in this study. As seen in the figure, the slope of the statistical fit corresponds much better with the data values, demonstrating a significant improvement in the estimation relationship accuracy of S/C density of nano- and microsatellites.
4.2 Reaction wheel mass estimation relationship

This example is about the development of a mass estimation relationship of a reaction wheel (including the wheel electronics) based on the stored angular momentum (H). From [13] we obtain a linear relationship, see Equation 4. The linear relationship developed in our study is given in Equation 5.

\[ M = 0.4 \times H + 2 \]  
\[ \text{SEE} = 57.2\% \]  \hspace{1cm} (kg) \hspace{1cm} \text{(4)}

Valid for: \( H < 10 \text{ Nms} \).

\[ M = 0.6771 \times H + 0.9534 \]  
\[ \text{SEE} = 52.7\% \]  \hspace{1cm} (kg) \hspace{1cm} \text{(5)}

Momentum range: \( 5.8 \times 10^{-4} \text{ Nms} – 4.2 \text{ Nms} \)

Figure 4 provides a visual comparison between the original relationship and the linear regression fit. The regression fit has a larger gradient and a much lower starting point than the original rule according to Equation (4). Part of the reason for the lower starting point can be the contribution of custom-built wheels seen as the data points in Figure 4 with the lowest mass values. Custom-built wheels for CubeSat missions typically come in the form of a Printed Circuit Board (PCB). The other data points in Figure 4 are commercial reaction wheels delivered as more complete packages including wiring and protective radiation shielding. The statistical fit generally predicts a lower reaction wheel mass than the original model. A reason for this can be because the original model was developed in 1999 and the reaction wheel data supporting this model was based on older and less efficient technology. The newly developed scaling rule better reflects the current solutions available on the market.

Figure 4: Comparison of original model with developed regression fit for estimating mass of a reaction wheel based on the stored angular momentum in the wheel

The original rule stated a linear relationship between reaction wheel mass and angular momentum. However, the best fit to the statistical data is a power-law curve with properties
as seen in Equation 6. The power-law coefficient of determination shows a 48% improvement compared with the $R^2$-value of 0.5806 for the linear regression fit. Based on these results it is recommended that the originally stated linear relationship is revised and a power-law fit is used for reaction wheel mass estimations.

$$M = 2.018 \times H^{0.4483}$$
$$R^2 = 0.8568 \quad [kg]$$
$$SEE = 49.1\%$$

There are many benefits of implementing design estimation relationships in the tool instead of using component selection from a database. These benefits are summarized in Table 2 along with some of the challenges met when using estimation relationships.

<table>
<thead>
<tr>
<th>Benefits:</th>
<th>Challenges:</th>
</tr>
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<tbody>
<tr>
<td>Flexibility with regards to various technology &amp; design solutions.</td>
<td>Continuously need new data to keep models up to date.</td>
</tr>
<tr>
<td>Minimizes the required number of user inputs.</td>
<td>Interpolation of data points may lead to a non-existing component (having characteristics between the statistical data points). However, it does give the user an indication of range of values the component characteristics should belong within.</td>
</tr>
<tr>
<td>Indicates general trends of design parameters, on component, subsystem and satellite level.</td>
<td>Some have rather large SEEs and lead to a broad range of possible solutions. Average values in these cases can be a misleading representation of actual possible design solutions.</td>
</tr>
<tr>
<td>Leads to faster design as user does not need to search through extensive component list to find applicable solution.</td>
<td></td>
</tr>
</tbody>
</table>

5. The design tool

A design tool, SCALES, has been developed [14] which estimates mass, volume and power values for all the relevant satellites subsystems. The tool asks for certain goal parameters, such as satellite mass, power consumption, linear dimensions and design maturity level. Based on these goal parameters, and a list of predefined values, the tool makes a conceptual design of all the satellite subsystems. Some of the primary outputs are the satellite mass and power budgets, along with an estimate of total volume and linear dimension. The tool is developed in MS Excel, as this provides a low threshold of usage due to that Excel is a commonly known software and readily available on most computers. Figure 5 shows the general architecture of SCALES. The green boxes represent different definitions of either tool users/usages or add-on help sheets. The add-on help sheets provide users with the ability to calculate necessary tool inputs or provide additional parameter analysis. The data flow through the tool is visualized using a colour-coding scheme signifying the different type of parameters. A multiple of design choices such as antenna type, satellite pointing direction, level of thermal control, link budget margin, modulation technique, attitude control actuators, and satellite shape are provided to the user generating a faster and more intuitive design process. In total there are 26 types of design choices implemented in the tool giving the users a total of 94 different options to choose from.
The tool described in this paper aims to solve the complex conceptual design problem of nano- and microsatellites in a fast and intuitive manner. With this tool a varied set of users can study the feasibility of different satellite design concepts and track the system- and subsystem-level changes occurring due to differing user inputs. Compared with other tools SCALES does not rely on component databases but is instead built-up with implemented estimation relationships especially developed for the smaller classes of satellites. Two examples of such scaling rules have been presented here and compared with design estimation relationships in other tools. A significant improvement in the estimation of S/C density and reaction wheel mass has been shown using statistical regression fits.

References