Constructions Mechanical and Thermal Conditions Modeling with GPU-based Approach

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Abstract. At present, there are two parallel trends related to spacecraft development tasks and problems. From the one side, due to complexity of constructions and growing use of high-power large-sized antennas, it is necessary to consider the effect of self-shading and research the effects accompanying this phenomenon. From the other side, modern computer tools, especially GPUs (graphics processing unit), allow one to create “mini-supercomputer” based on “common” desktop/laptop and perform CAE (computer-aided engineering)-based processes using 3D models of different LOD (Level-of-detail). In this paper, we present a conception of SA parameters computer modeling based on hierarchical, property-based 3D-model of spacecraft. Thus, one can model different work modes of spacecraft on the project stage, with real-time prediction of effects related to space factors complex combination impact. The result is easy-to-edit, easy-to-calibrate “digital twin” of spacecraft which allows engineer to model and investigate complex space factors combination results for a different orbital work mode.

1. Introduction

At present, specialists in spacecrafts design and engineering face with new tasks and problems, such as (see, e.g., reports and books [1]-[3]):

- Significant increase in energetical requirements for spacecraft;
- Potentially complex shading of the spacecraft and SA surface during lifecycle;
- The need to account different space factors at the design stage;
- The need in the ground experimental testing infrastructure development and evolution.

On the other side, modern technologies provide more opportunities to work with these problems, such as:

- Significant progress and cheapening of heterogeneous computing devices;
- Development and progress of parallel and heterogeneous computing algorithms.

Thus, one has an opportunity to perform real-time computer testing of spacecrafts subsystems at the design stage using desktop / laptop with the corresponding GPU device (see books [4], [5] for GPU usage in computer modeling and ray-tracing technologies [6], [7] usage in realistic rendering)

2. Methods. GPU Computing and “Digital twin of Spacecraft
Thus, one has an opportunity to perform real-time computer testing of spacecrafts subsystems at the design stage using desktop / laptop with the corresponding GPU device. The main stages of process are shown at Figure 1.

![Computer modeling functional scheme](image)

Thus, we obtain so-called "digital twin" ("digital copy", "digital shadow") of real spacecraft, with opportunity to model different situations related to orbital work and to find ways to overcome possible problems.

3. Results. GPU-based Approach Application for SA Modeling and Project Analysis

The main interest of such version of GPU-based approach is its universality – processes related to ray-tracing interpretation (i.e. everything involving 3D-primitives intersection, relative positioning etc.) might be model in the terms of such approach with error based mostly on 3D model level of detail, number of rays generated by impact source and their distribution.
Figure 2: An example of heatmap generated for finite-elements model of spacecraft based on its orbit parameters and materials properties

An example of such approach is shown on Figure 3 – shadow modeling of SA related to spacecraft with large-scaled communication antennas during GEO (geosynchronous equatorial orbit) orbital work. Operator can modify all geometrical properties, thermal coefficients etc. to provide virtual experiments and "test" spacecraft model. Current experiments is related to one of important problems - thermal waves along solar panels of GEO satellites with large difference between lower and upper bounds of temperature.
Figure 3: Shadow and heat waves modeling (snapshots time step is equal to 20 minutes, standard heat colour map is used)

In related example, ray-tracing is used, i.e. to compute coefficients in the following heat balance equation:

$$
\frac{dT_i}{dt} = \sum_{j=0}^{n} \lambda_{ij} \frac{l_{ij}}{F_i} (T_i - T_j) - \sum_{j=0}^{n} \frac{H_{ij}}{F_j} \left( \frac{\sigma}{\epsilon_j} \left[ \frac{1}{\epsilon_j} \right] \right) F_j \left( 0.01T_i^4 - F_i \left( 0.01T_j^4 \right) \right)
$$

where

- $T_i$ - temperature of i-th finite element of spacecraft hierarchical model at time $t$,
- $c_i$ - heat capacity of i-th element,
- $Q_{in}^i(t), Q_{out}^i(t)$ - heat flows from inner (crew, engines etc.) and outer (Sun, Earth etc.) sources,
- $\lambda_{ij}$ - thermal conductivity of the material at the boundary of i-th and j-th finite elements,
- $l_{ij}$ - distance at which the temperature difference $T_i - T_j$ is observed
- $F_{ij}$ - cross-sectional area of i-th and j-th finite elements,
- $F_i$ - surface area of the i-th radiating element
- $\sigma$ - Stefan-Boltzmann constant,
- $\epsilon_j$ - "gray body" blackness,
- $H_{ij}$ - i-th and j-th elements mutual irradiation area - we compute it with ray-tracing technics.

4. Discussion. Possible Applications

4.1. Solar arrays power production modeling

Figure 4 demonstrates modeling results related to works [8],[9]. Here, according to scheme on Figure 1, we use finite elements model of International Space Station (ISS) with translation and rotation properties of each element and orbital movement ODEs (ordinary differential equations) IC (initial conditions) / orbital elements provided with TLE (two-line elements) files to create "temporal profile". Then, using solar array configuration file, we form input of ray-tracing library to compute shadow environment and model power production of solar batteries.
4.2. Illumination modeling

Figure 6 demonstrates results of modeling where, according to scheme on Figure 1, we use finite elements model of crew module with light sources. Using model editor operator forms distribution of light units and properties of every unit. Then we form input of ray-tracing library to model illumination at each point of module.
Figure 6: An example of illumination modeling for spacecraft interior based on finite elements model, light sources configuration and material properties to model illumination map.

Figure 7 demonstrates configuration file used to create illuminance model.

```xml
c<xml version="1.0" encoding="UTF-8" ?>
  <tracerConfig>
    <modelPath path="Example.skp"/>
    <traceFParams sqrtNumSamples="2" timeout="10" maxDepth="100" numPointSamples="10" beginDepth="2"/>
    <camera>
      <eye x="-6780.49" y="-153.231" z="223.46"/>
      <lookAt x="-3770.59" y="-153.231" z="223.46"/>
      <up x="0" y="0" z="1"/>
      <fov w="45" h="45"/>
    </camera>
    <points>
      <point normMax="-1" normMin="-1" name="0">
        <position x="-3936.66" y="-361.189" z="-661.599"/>
        <normal x="0" y="0" z="1"/>
      </point>
      <point normMax="-1" normMin="-1" name="1">
        <position x="-2872.26" y="-520" z="-798.908"/>
        <normal x="0" y="1" z="0"/>
      </point>
    </points>
  </tracerConfig>
```

Figure 7: An example of configuration file for illuminance modeling.
Described approach might be used to model different modes of orbital work, i.e. ERS (Earth remote sensing) [10],[11], and also to provide total modeling of satellite constellations from spacecraft subsystem to the total cluster.

5. Conclusions

We present a GPU-based approach to space factors modeling during spacecraft design process. This approach allows to perform real-time modeling using LOD-based models with materials parameters set. Models are processed with ray tracing subroutines and GPU usage, which allows to increase computation speed and optimize memory usage. Modeling approach is universal it the sense that it allows to model factor impacts related to 3D models relative positioning, relative shadowing etc. Thus, suggested modeling approach allows one to create easy-to-edit and easy-to-calibrate “digital twin” of spacecraft or other mechanical construction, which is an efficient tool to investigate impact of complex combination of outer and inner factors.

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