SIMULATION OF THE ON-ORBIT CONSTRUCTION OF STRUCTURAL VARIABLE MODULAR SPACECRAFT BY ROBOTS

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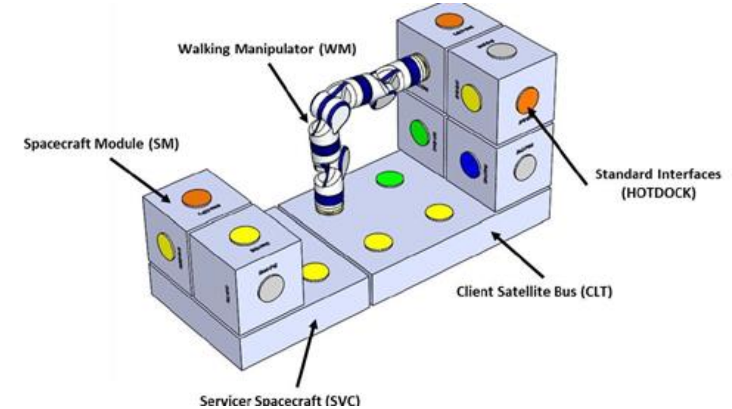
Motivation and Introduction

Robotic construction of future advanced spacecraft and orbital platforms on-orbit

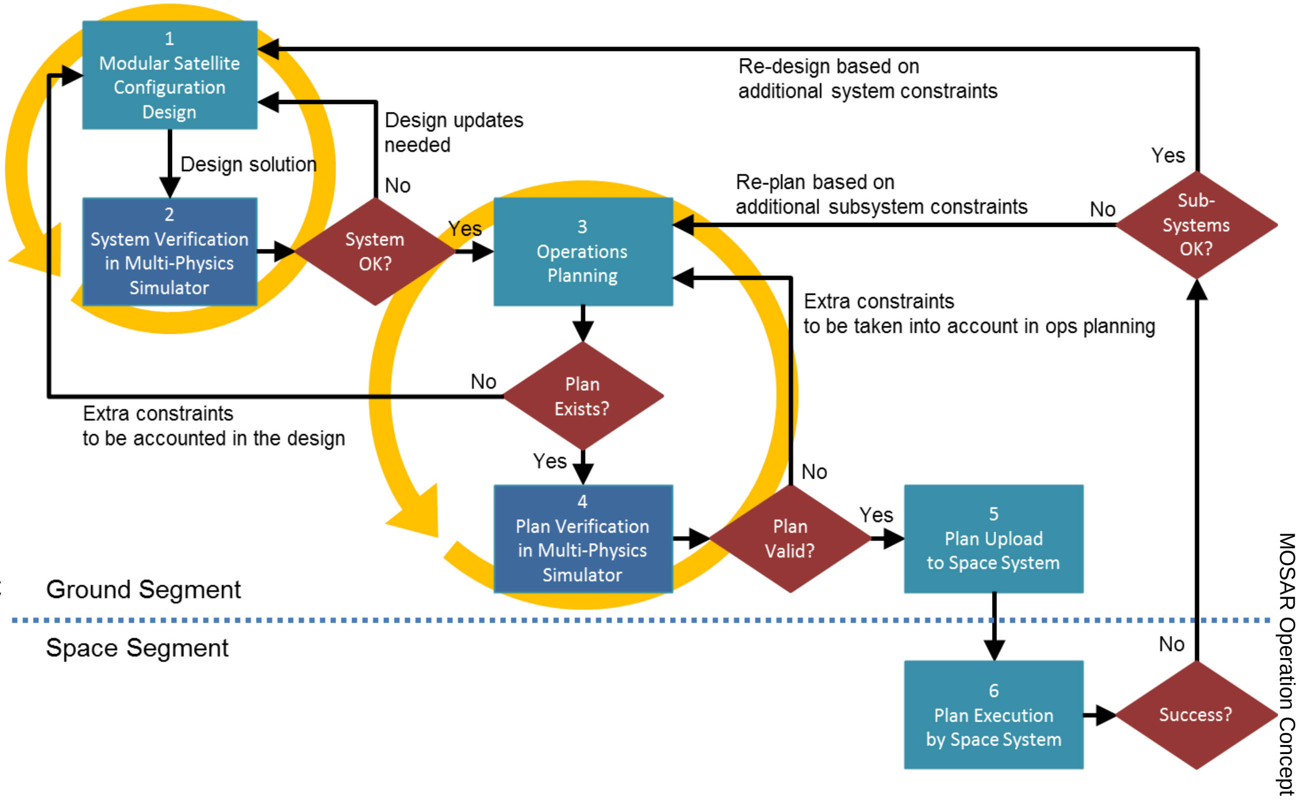
Multi Arm Robot Concept	Modular Satellite Concept	Ground demonstrator



- Motivation: Large space structures (e.g. large antennas) or desired modularity (e.g. change payload with same satellite bus)
- Satellite platform technology moves at a much slower pace than payload (commercial trends)
- Standard interfaces (SI or Hotdock) on spacecraft, modules and robot provide mechanical, data, power and thermal transfer
- Symmetric robot arms (with SIs on each side) can „walk“ over SIs and transfer modules

Project Introduction

- **EU MOSAR** (Modular and Re-Configurable Spacecraft)
  - Development of ground demonstrator for on-orbit modular and re-configurable satellites as well as the supporting software and control system
  - 7-DOF Walking Manipulator Robot (WM)
- **ESA MIRROR** (Multi-arm Installation Robot for Readying ORUS and Reflectors)
  - Development of ground simulator for on-orbit assembly of a large reflector consisting of hexagonal shaped modules
  - Multi-Arm Robot (MAR) composed of three robotic subsystems: A torso and two symmetrical 7-degree arms (based on WM design)

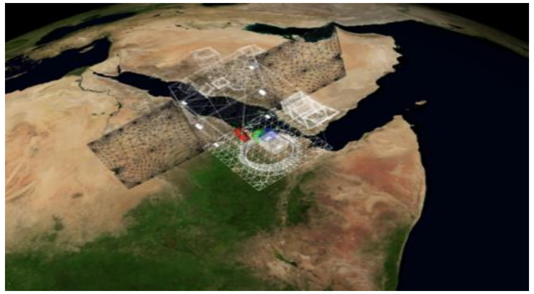


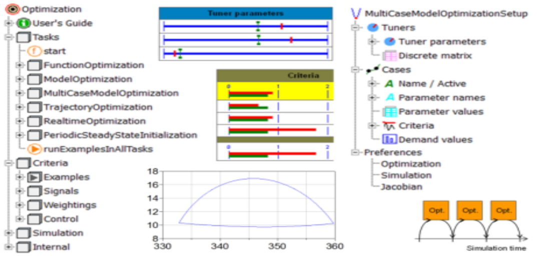
- DLR-SR was responsible for the development of a simulation environment offering assistance for module design, system configuration and operation planning, with the support of a multi-physics engine within these projects → Focus of presentation

Object-oriented Modeling with Modelica

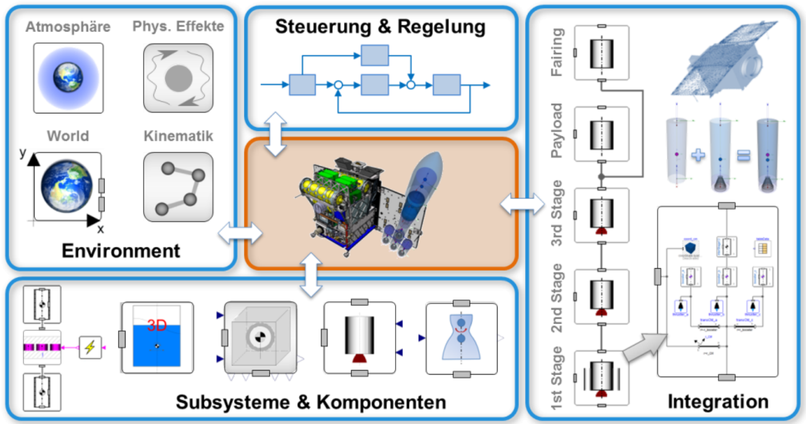
- DLR-SR has developed over many years libraries relevant the scenarios:

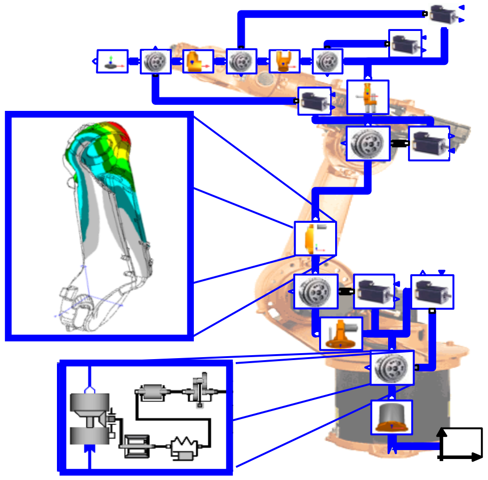
- **Modelica SpaceSystems & Environment Library**
  - Modeling of environment and orbit
  - Actuator and sensor models
- **Modelica Robots & RobotDynamics Library**
  - Robot models
  - Kinematic & Dynamic
- **Supporting Modelica Libraries**
  - Multi-body, FlexibleBodies, Visualization, Optimization

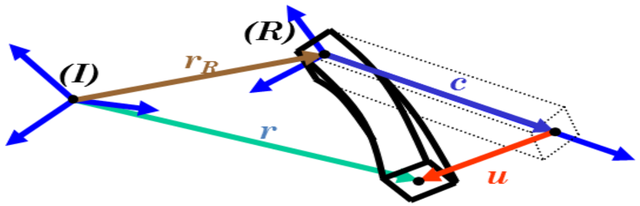




DLR-SR Modelica Libraries







Key challenges for the simulation

- **Complex structural variable systems consisting of modular satellite or array components.**
- **Modelica does not directly support structural variable systems**
  - The number of states must be constant during the simulation.
- **Hybrid and stiff systems with discrete and continuous parts**
  - The discrete elements result from the switching behavior of the SIs and algorithms for the control logic
- **Many disciplines involved**
  - e.g. power and thermal management, robot control, and orbital mechanics
- **Dynamic robot arm docking and pick & place operations**
  - High number of potential connection points
  - Torso robot connected to two robot arms which results in a robot with 2*7+1=15 DoF.

- New approach necessary for the efficient and fast simulation
- For early concept studies simulation speed important
- Interaction with trajectory planning and control tools from other project partners

Model Development using controllable constraints

- **Standard solution**: The preferred solution for systems with a limited total number of configurations and with a limited number of configuration switches is the preparation of independent models for each configuration which are run sequentially.
- **Problem**: In the scenarios, both the number of configurations and the number of configuration switches exceeds a reasonable number of predefined model architectures
- **Custom Solution**: For a moderate number of configurations, the preferred method is working with controllable constraints
  - Constraint will switch from “free motion” to “rigidly connected” (identical position, velocity, and acceleration).
  - The implemented is based on method using force constraints with a variant of the Baumgarte stabilization

```
if not constrained then
  f_c = {0,0,0};
else
  g_con_ddot +
  2*eta*g_con_dot + eta*eta
  *(g_con - pos_offset) = {0,0,0};
end if;
```

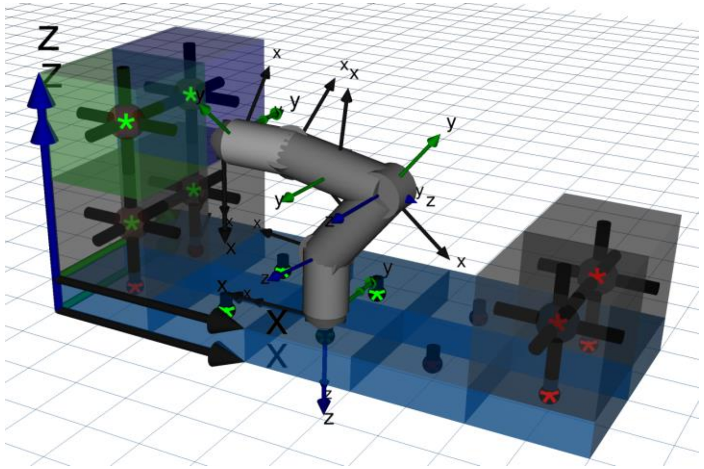
Problem:

- Extrapolating this technique to systems with a high number of switchable connectors leads to huge stiff differential equation systems (high computational load)

Tensor body models

Configurations of module stack are realized by tensor body models

- Modifiable rigid bodies, consisting of individual sub-components
- Can change their inertia, mass and geometric shape
- Allow for activating and deactivating grid elements and also consider orientation and connectors of each individual component
- A special connection algorithm can check if an electrical connection can exist between the modules.
- The (simplified) thermal balance is also computed: The thermal capacity and thermal resistance of the connectors is updated depending on the current configuration

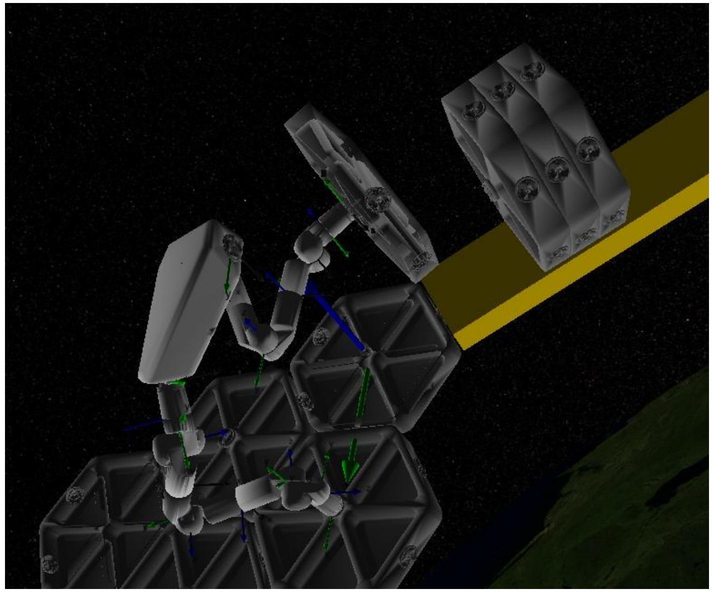


Tensor body models

- Variable structure models developed to significantly reduce the number of objects that need to be computed
- Modifiable rigid bodies, which are consisting of individual sub-components and can change their inertia, mass and geometric shape

Robot Pick & Place Operation using Tensor body models

- A logical algorithm in the simulation model triggers events which tensor bodies are involved and how they should be changed.
- For a pick & place operation this leads to the re-computation of the properties of the main satellite tensor body, as well as the corresponding tensor body at an end effector on one of the robot arms.
- Since after a pick & place operation, it can occur that no module can be left at an end effector of a robot, a very small (dummy) mass and inertia are used to approximate this.
- Since all involved tensor bodies are updated and recalculated with the same event at the same time, no discontinuities can occur, and the total mass always stays constant.

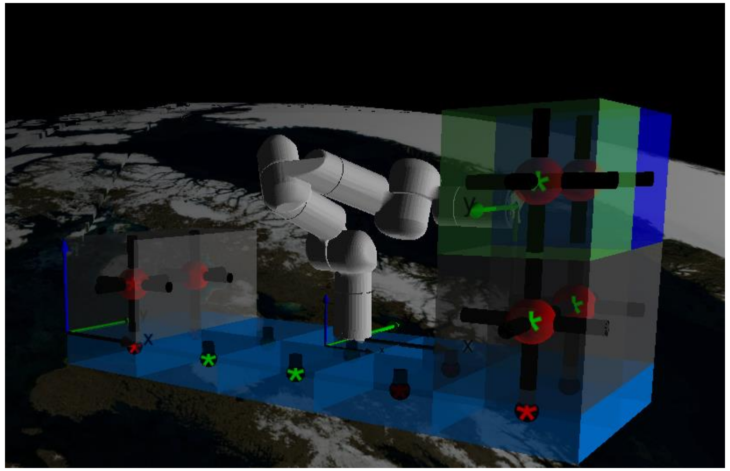


Robot Pick & Place operation:

1. The robot moves to the location of the module, ready to grasp the module
2. The module is unfixed from the spacecraft and connected to the robot using the SIs
3. The robot moves the module to the desired location
4. The module is fixed at its new position via one or more SIs and disconnected from the robot SI.

Complete Modeling Overview

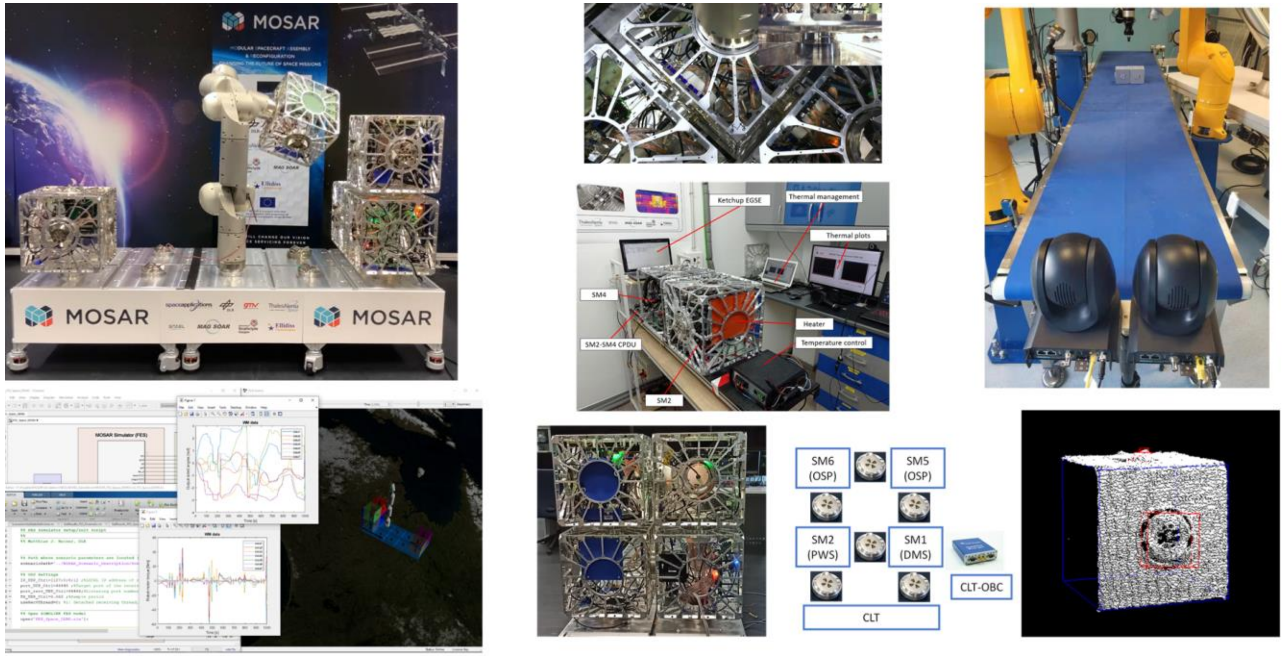
- **Variable module design using Tensor Body models**
  - Individual mass, inertia, orientation and connectors (SI)
  - Heat & power transfer properties (simplified)
- **Detailed orbit model**
  - Full orbit dynamic, including Sun and Moon
  - Surface heat model (Solar, Albedo, Planet IR and Deep Space Radiation)
- **Surface contact model with friction**
  - Contact forces between robot TCP, modules and platform are considered
  - Dynamically updated using tensor state
- **Satellite attitude controller (GNC system)**
- **Detailed WM robot model:**
  - Robot geometry from URDF data (mass/inertia data and kinematics)
  - Powertrain model
    - motor brake, nonlinear flexible joint model gearbox with friction
    - Joint position & torque controller
- **UDP Interface for simulator to communicate with external partner**
  - Cartesian Robot control & Trajectory planning
  - Blocking UDP for synchronization



Visualization generated directly by the Modelica model using **DLR SimVIS** and the **DLR Visualization Library**

MOSAR Demonstrator Overview

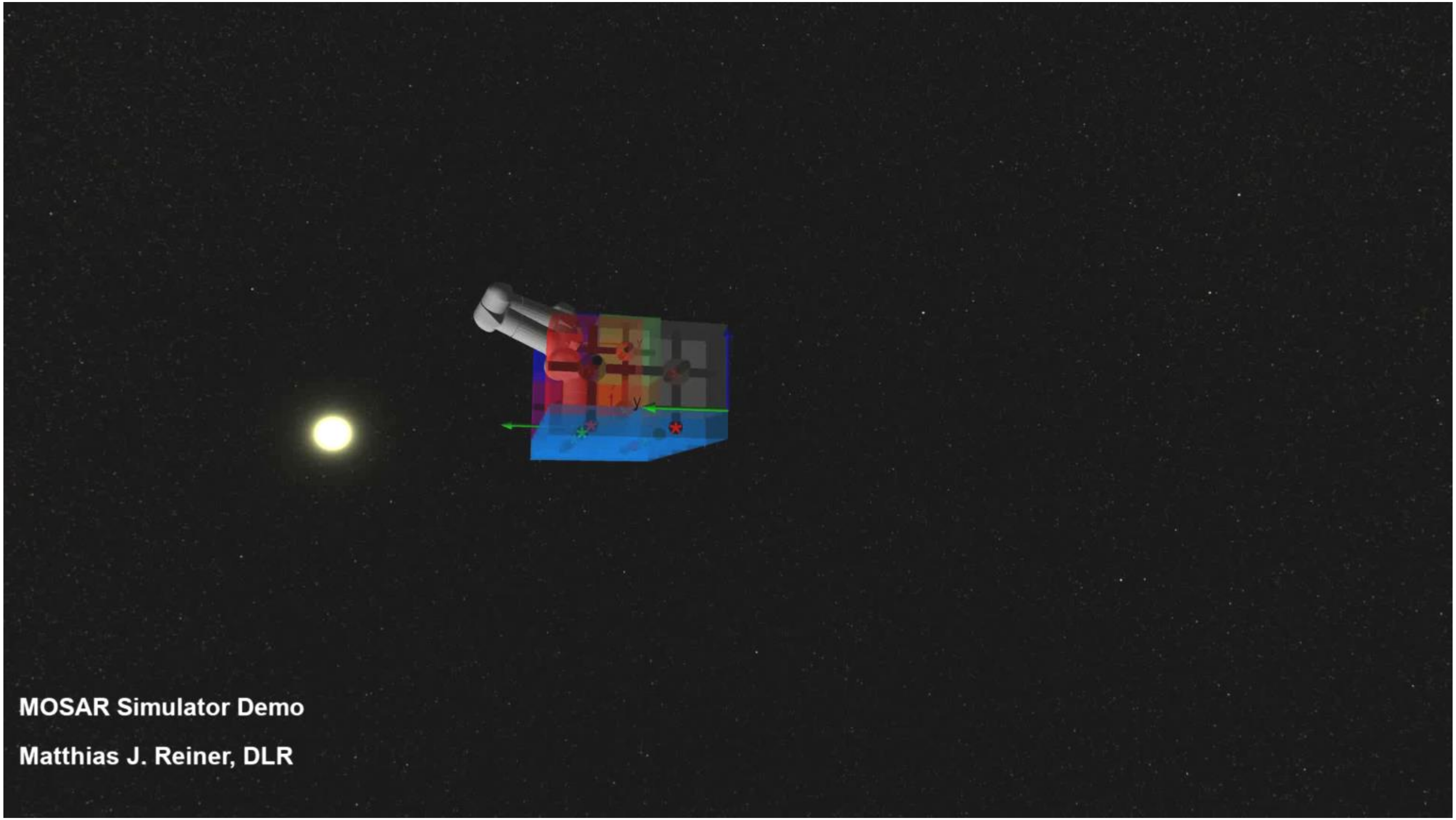
- **Demonstrator setup for the MOSAR project:**
  - Physical assembly of prototype modules and the Walking Manipulator (WM)
  - Simulator and Design Tool based on simulator
  - Cartesian WM controller
  - Collision free path planning tool
- **Test scenario: Satellite reconfiguration**
  - Definition of starting and desired end configurations of the module stacks using Design tool
  - Planning algorithm uses configuration information to plan a sequence of operations for the WM and the SI connectors to move the modules collision free from the starting to desired end configuration.
  - The planning module communicates with a high-level robot controller.
  - This controller can communicate with the simulator as well as the real hardware setup
  - To ensure the safe operation and to validate the operation plan the complete sequence is simulated using the simulator first, before moving the real hardware.



Results from MOSAR project partners: SpaceApps, GMV, MAGSOAR, Thales Alenia Space (France and UK), SITAEL, Elidiss Technologies, University of Strathclyde, Glasgow and DLR

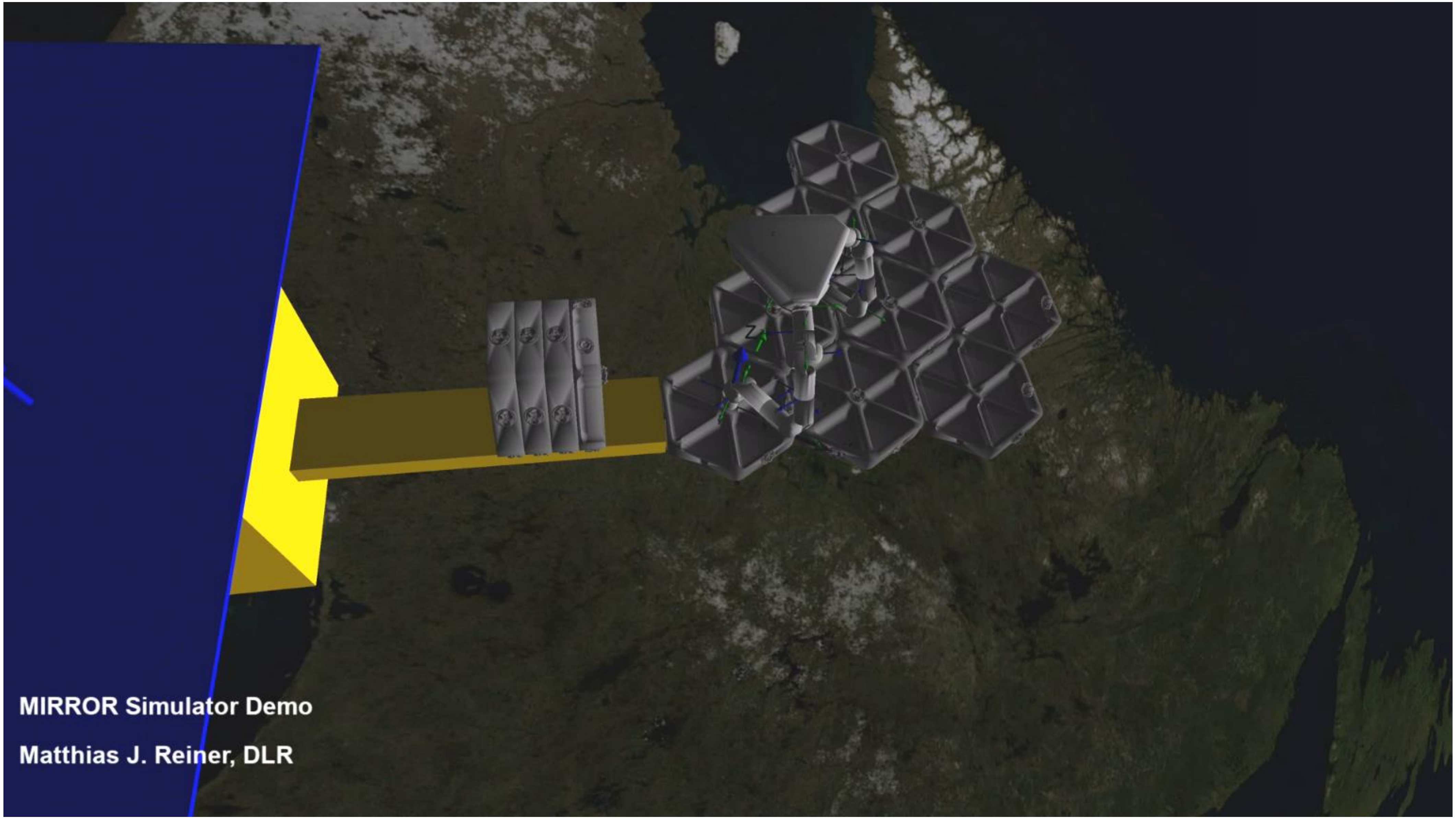
- Physical demonstrator setup with the WM relocating an SM.
- SIs and a thermal testing setup.
- Setup for the visual damage inspection of the modules.
- Screenshot of the MATLAB interface of the simulator

MOSAR Simulator Demo



Speed-Up Test Trajectory

MIRROR Simulator Demo



Speed-Up Test Trajectory

Conclusions and outlook

- Simulation of the complex scenarios in Modelica was possible using the tensor body concept for the structural variable module stack, and integration of previously developed Modelica libraries at DLR-SR.
- The MOSAR project could be successfully be finished using the new approach.
- The concept was also used in the MIRROR project which enabled a very fast development time
- With small adaptations could also be used for many similar applications both on-orbit as well as on earth (e.g. building construction).
- However, the tensor body concept and switchable force constraints also lead to a significant increase in the overall model complexity (especially the required logical parts) and some approximations and simplifications are necessary and restrict what is possible to simulate.
- An extension of the Modelica language (and simulation tools) to directly handle structural variable systems or new developments within similar languages such as the modeling language Modia could improve this aspect in the future

Imprint

Topic: **Modelica Conference 2022 --Simulation of the on-orbit construction of structural variable modular spacecraft by robots**

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