# Appendix N

## The Thermal Design of the KONTUR-2 Force Feedback Joystick

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**Abstract**

The KONTUR-2 Mission is a cooperation between the German Aerospace Center (DLR), ROSKOSMOS, RSC Energia and the Russian State Scientific Center for Robotics and Technical Cybernetics (RTC). Its purpose is to study the feasibility of using teleoperation to control robots for tasks such as remote planetary explorations. The operating human would be stationed in orbit around the celestial body in a spacecraft. For KONTUR-2, the earth is utilized as the celestial body, and the ISS as the spacecraft with the ISS crewmember as the operator. The main goals of this mission are the development of a space-qualified 2 degrees of freedom (DoF) force feedback joystick as the human machine interface (HMI), the study and implementation of underlying technologies to enable telepresence in space, and the analysis of telemanipulation performance of robotic systems. The DLR KONTUR force feedback joystick was upmassed and installed in the Russian Service Module of the ISS in August 2015. The first of a series of experiments to be completed by December 2016, were carried out successfully.

Meeting the thermal requirements of the joystick is one of the key challenges in the KONTUR-2 Mission. This presentation focuses on the thermal design for the force feedback joystick to cope with the unique conditions in a manned spacecraft. In order to reduce complexity, and further improve safety aspects for the integration on board the Russian segment of the ISS, active cooling has been eliminated in the force feedback joystick. Furthermore, as a safety measure, a temperature control system (TCS) has been developed and implemented able to respond to all unforeseen disturbances.

This presentation outlines DLR's approach to handle the unpredictable thermal output of the mechatronic system, resulted from a complex combination of the specific task, and the operating handling of the Cosmonaut. This in turn directly influenced the design to meet the mission's requirements, which includes the physical human-joystick interaction, storage on board the ISS, electronic components, operation time, and system performance.

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# The Thermal Design of the KONTUR-2 Force Feedback Joystick

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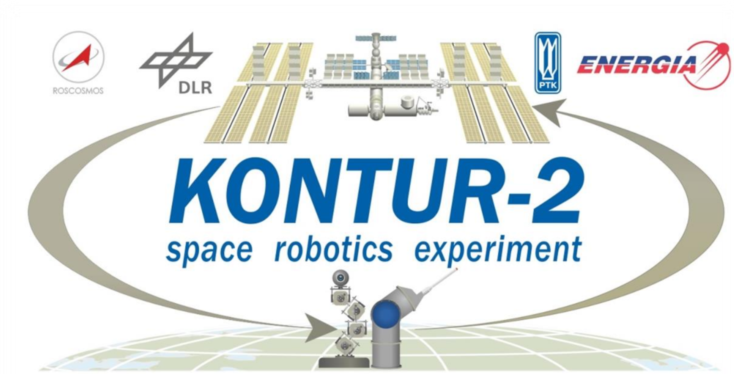


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## Outline

- KONTUR-2 mission overview
- Thermal requirements
- Thermal design
- Analysis cases and results
- Temperature Control System (TCS)
- Thermal test and results
- Conclusion and Outlook

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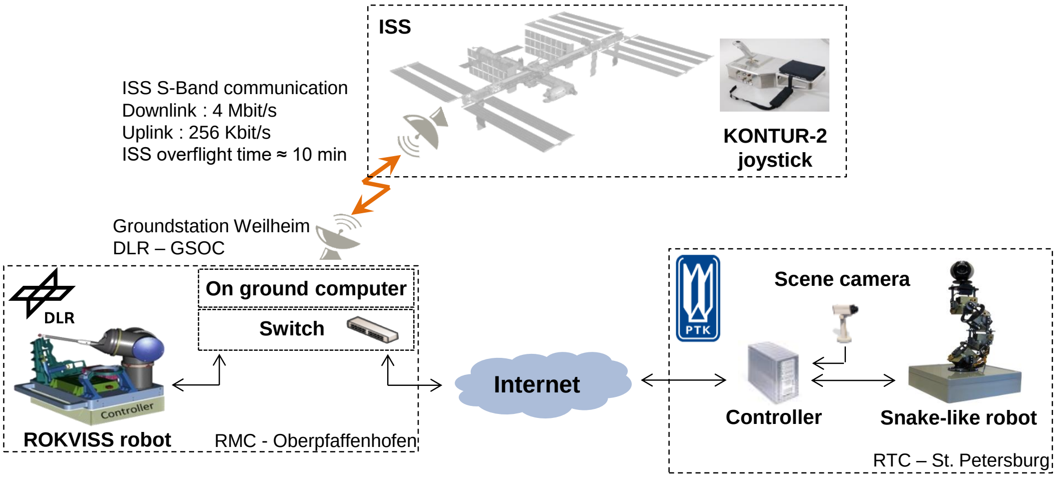
## KONTUR-2 mission overview




### Feasibility study

Telepresence for remote planetary exploration

### Experiment scenario

Teleoperating robot on the planetary surface from orbit



## KONTUR-2 mission overview

### Goals

- Development of a space-qualified force feedback joystick as the human machine interface (HMI)
- Development of telepresence technologies
- Study of ergonomics and human factors of the force feedback in microgravity

### Joystick specifications

- Maximum force on joystick handle: 15 N
- Workspace: +/- 20°
- 2 Degrees of freedom

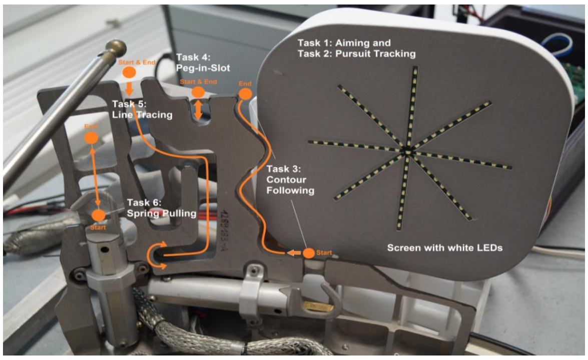
### History: ROKVISS experiment

- Verification of robotic components in space


KONTUR-2 Joystick in Operation Mode


ROKVISS robot on board the ISS

## KONTUR-2 challenges




KONTUR-2 task board of the ROKVISS robot

Cosmonaut O. Kononenko performs a task on ISS

Difficult thermal conditions

Unpredictable motor load, which is a complex combination of

- Different tasks
- Operating behavior of the cosmonaut
- Side effects e.g. telepresence performance, friction modeling



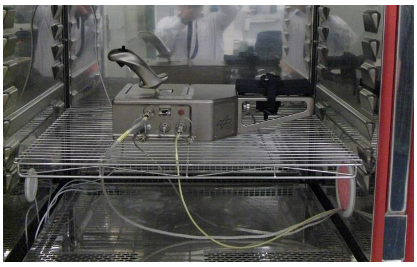
## Thermal requirements

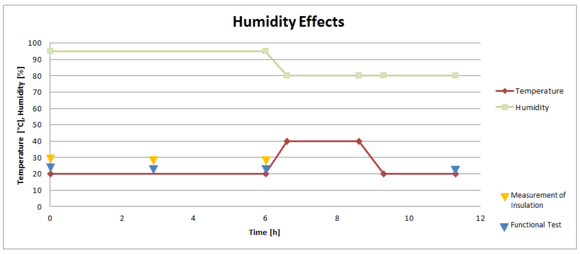
Requirements

- Joystick housing maximum allowable temperature: 40°C
- Operational temperature range of on-board electronics and motors
- No active cooling system
- Continuous operating time: 30 minutes

Environmental qualification tests

- Humidity cycles
- Temperature cycles
- Offgassing (toxicity)





## Thermal design - model

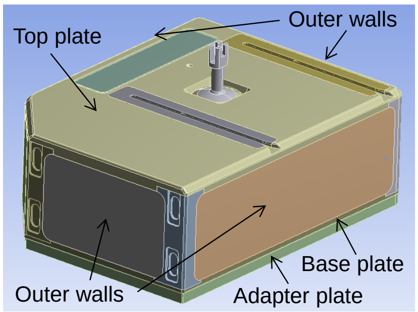
- FEM analysis (ANSYS 14.0)
- No printed circuit boards (PCBs)

### General boundary conditions

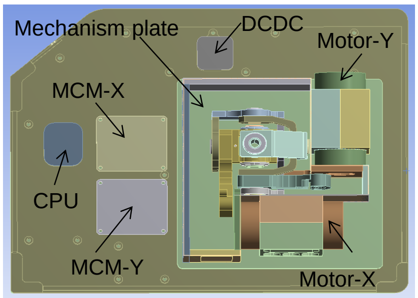
- ISS ambient temperature condition ≤ 28°C
- Complete insulation between joystick and ISS structure
- Heat flows with +10% margin

### Conductive boundary conditions

- Air inside the joystick appeals thermoconductive (neglected)
- Ideal thermal contact between mechanical parts
- Electronic components attached to the mechanical parts through interface materials (gap pads)




Joystick housing FEM model (ANSYS)




Joystick components inside

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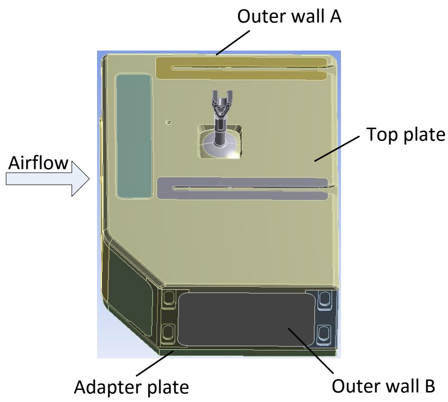
## Thermal design - model

### Radiative boundary conditions

- Heat radiation exchange in the environment
  - → Joystick housing with electroplated chromium coating: ε=0.1
  - → Adapter plate with black anodized aluminium: ε=0.82
- Heat radiation exchange inside the joystick

### Convective boundary conditions

- Airflow (0,05 m/s) of the ISS air supply near the joystick
  - → Similitude model of a plane plate in a longitudinal flow for specific plates and walls (worst case)




ISS supply airflow direction with respected plates and walls

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## Thermal design – analysis cases

Analysis cases based on states

### Standby

- Initial state after switching on and booting
- Passive mode – only communication possible
- Intended as pause mode

| Electric Components | States | | |
|---|---|---|---|
| | **Standby** | **Idle** | **Operation** |
| **Motors** | None | None | Load-depending |
| **Motor Control Module (MCM)** | None | ≈ 3.5 W | Load-depending |
| **DCDC-Converter** | ≈ 1.9 W | ≈ 1.9 W | ≈ 1.9 W |
| **Microcontroller Module (CPU)** | ≈ 5.0 W | ≈ 5.0 W | ≈ 5.0 W |

Heat dissipation for basic states of the joystick

### Idle

- Joystick is calibrated
- Motor Control Modules (MCM) are active but no torque is commanded
- Intermediate state between standby and operation

### Operation

- All hard- and software components are active including force feedback control

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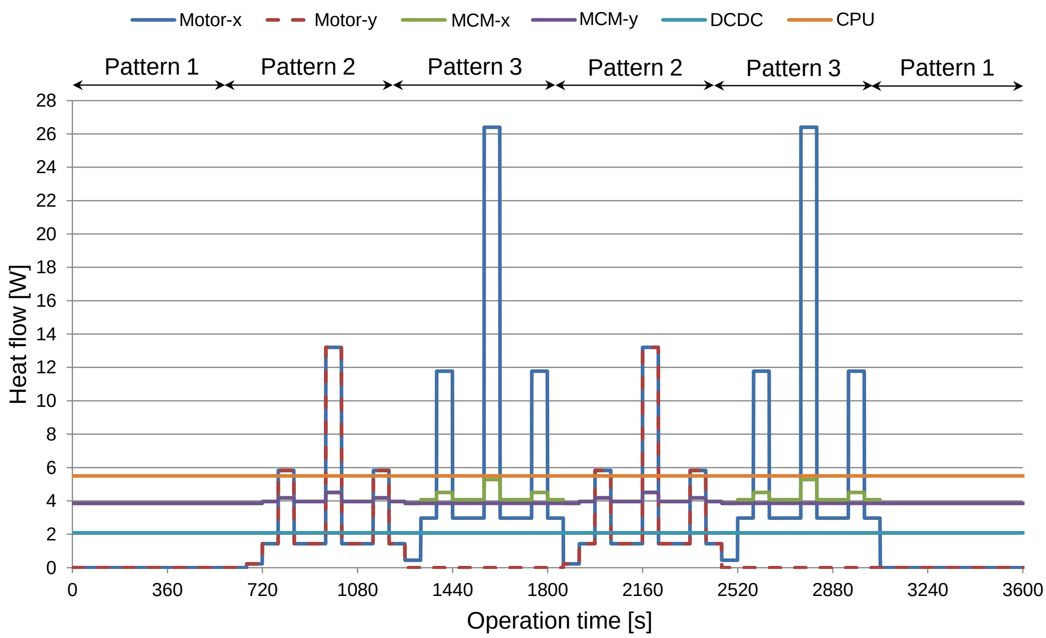
## Thermal design – analysis cases

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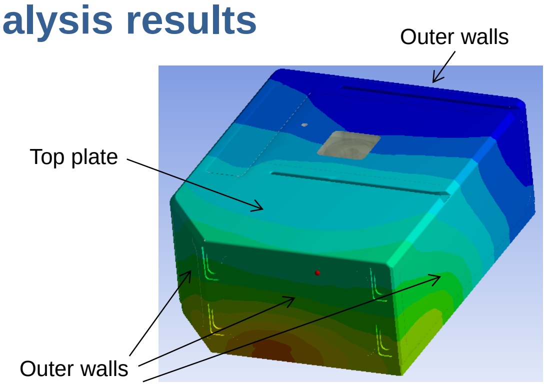
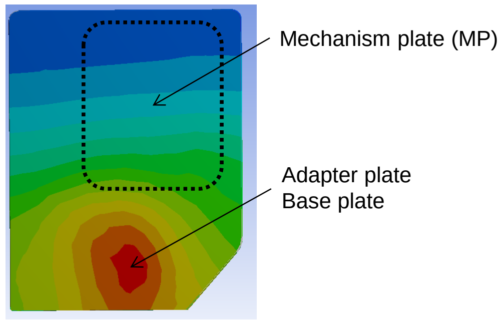
## Analysis results



Characteristic joystick temperature distribution from the front side



Characteristic hotspot from bottom side

| Housing location | Standby | Idle | Operation | | |
|---|---|---|---|---|---|
| | Steady state > 5 h | Steady state > 2 h | 30 min | 60 min | 30 min (without adapter plate) |
| | °C | °C | °C | °C | °C |
| **Base plate** | 37.70 | 46.38 | 34.60 | 38.64 | 40.00 |
| **Adapter plate** | 37.64 | 46.32 | 34.55 | 38.58 | – |
| **Outer walls** | 37.49 | 46.03 | 34.27 | 38.65 | 38.66 |
| **Mechanism plate** | 36.83 | 45.29 | 33.53 | 37.48 | 37.17 |
| **Top plate** | 36.68 | 44.72 | 33.10 | 37.00 | 36.10 |

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## Temperature Control System (TCS)

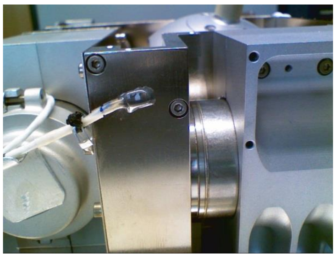
Objectives

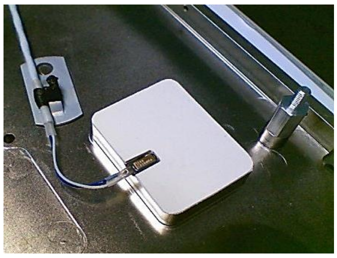
1. Observance of the temperature limits for the electronic components
2. Observance of max. housing temperature

   → Even when the joystick is operated incorrectly

- 9 temperature sensors are monitored every 1 sec.


Temperature sensor of one motor housing


Temperature sensor T_Case near the top plate of the the joystick housing


Temperature sensor near the CPU

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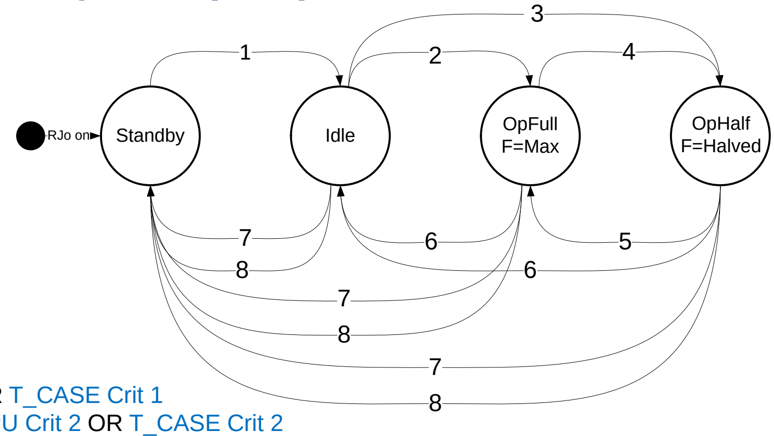
## Temperature Control System (TCS)




→ Additional state: OpHalf

**Statemachine conditions**

1: Calibrate AND T_CPU Crit 1 OR T_CASE Crit 1
2: Application activated AND T_CPU Crit 2 OR T_CASE Crit 2
3: Application activated AND T_CPU Crit 3 OR T_CASE Crit 3
4: T_CPU Crit 4 OR T_CASE Crit 4
5: T_CPU Crit 5 OR T_CASE Crit 5
6: Application deactivated
7: Standby
8: T_CPU Crit 8 OR T_CASE Crit 8

If T_CPU is invalid use T_DCDC
If T_CASE is invalid use T_MotorX OR T_MotorY

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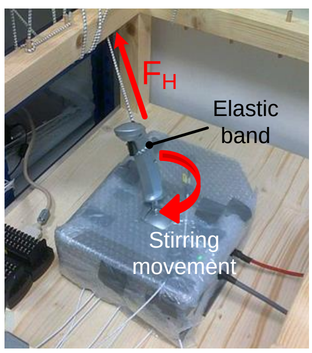
## Thermal test

Test cases

1. Standby state until steady state
2. Idle state until TCS switches to standby state
3. Operational state (stirring) with elastic band
   a. $F_H = 5$ N
   b. $F_H = 10$ N
   c. $F_H = 15$ N (max. force)
   → Higher load than normal usage!

- Joystick in thermal chamber
- No adapter plate
- Worst case ambient temperature is 28°C
- Housing isolated with polystyrene, foam and bubble wrap to reduce convectional heat transfer

Isolated joystick




Stirring demo

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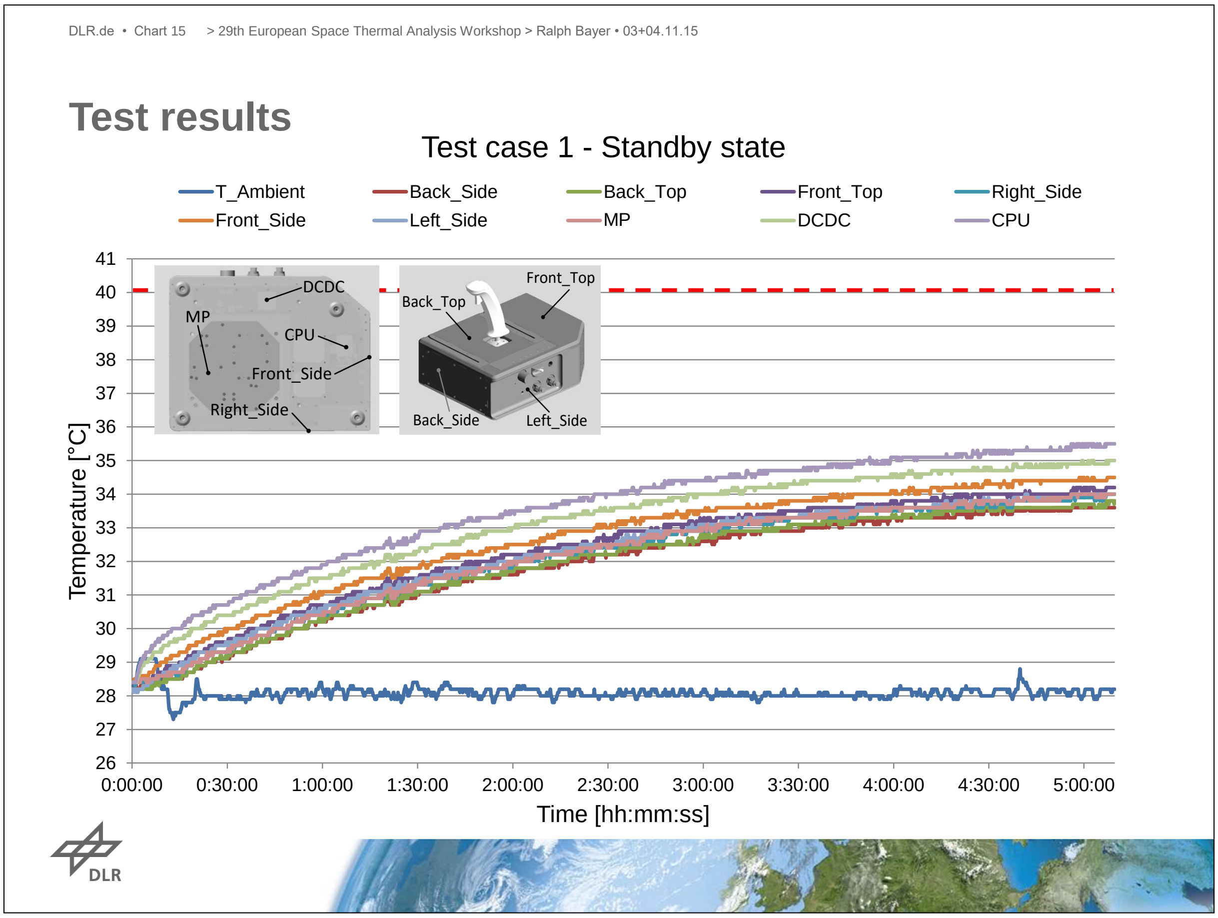
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Test results
Test case 1 - Standby state
T_Ambient
Back_Side
Back_Top
Front_Top
Right_Side
Front_Side
Left_Side
MP
DCDC
CPU
DCDC
MP
CPU
Front_Side
Right_Side
Front_Top
Back_Top
Back_Side
Left_Side
Temperature [°C]
Time [hh:mm:ss]
0:00:00
0:30:00
1:00:00
1:30:00
2:00:00
2:30:00
3:00:00
3:30:00
4:00:00
4:30:00
5:00:00
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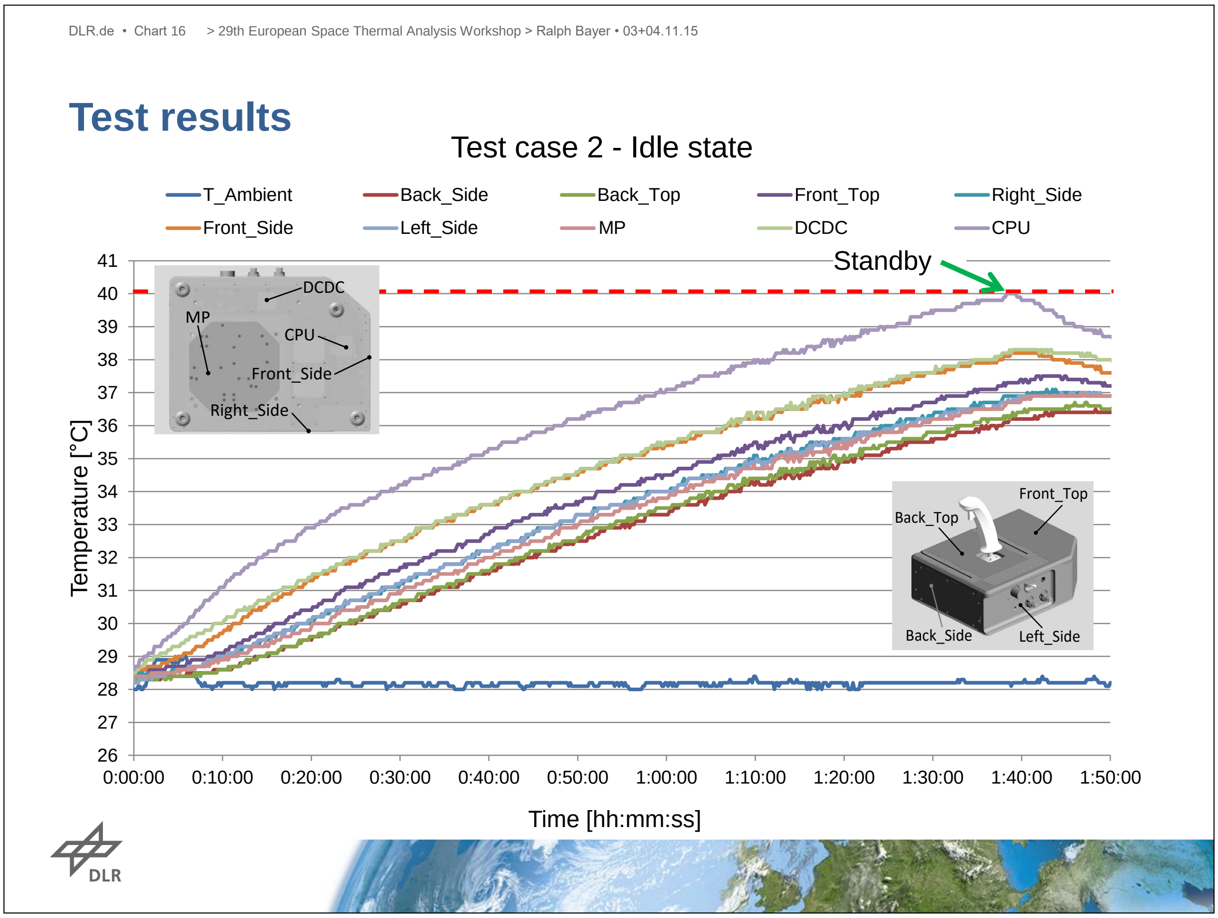
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Test results
Test case 2 - Idle state
T_Ambient
Back_Side
Back_Top
Front_Top
Right_Side
Front_Side
Left_Side
MP
DCDC
CPU
Standby
DCDC
MP
CPU
Front_Side
Right_Side
Front_Top
Back_Top
Back_Side
Left_Side
Temperature [°C]
Time [hh:mm:ss]
0:00:00
0:10:00
0:20:00
0:30:00
0:40:00
0:50:00
1:00:00
1:10:00
1:20:00
1:30:00
1:40:00
1:50:00
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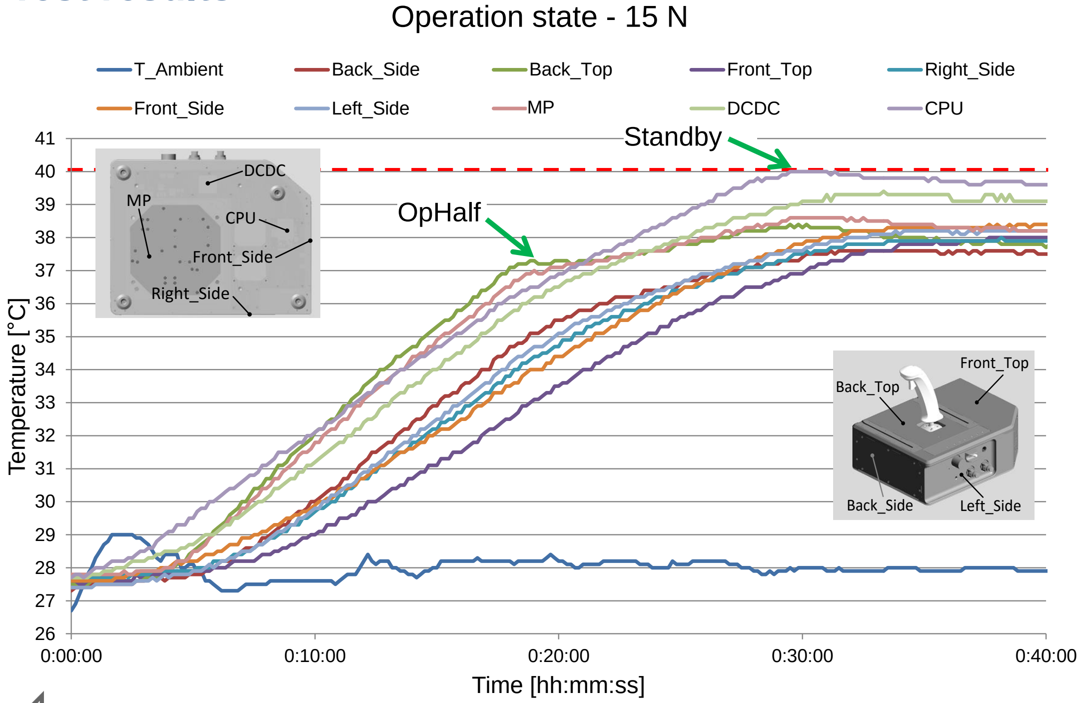
## Test results

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## Conclusion

Thermal design

- The thermal analysis model has been verified by thermal tests
- Thermal test have clearly proven that the joystick fulfills all thermal requirements under the assumed boundary conditions.
- The TCS has successfully been developed, implemented and tested.
- All environmental qualification and acceptance tests have been passed

KONTUR-2 mission

- The force feedback joystick was installed in the Russian service module in August 2015
- First experiments were conducted successfully

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## Outlook

- KONTUR-2 joystick shall operate until December 2015 on board the ISS
- During ongoing experiments all performance data will be recorded for each session
  → Ergonomic study for using force feedback in microgravital environment
  → Study of space related telepresence control performance
  → Evaluation of TCS-Concept for other robots
  → Further verification of thermal FEM-model

Haptics experiment with telepresence from space:

Handshake between cosmonaut on board the ISS and earth representative planned in December 2015

Cosmonaut handshake training with the KONTUR-2 joystick engineering model and the DLR humanoid robot Justin between the cosmonauts G. Padalka and O. Kononenko

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# Thank you for your attention!

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### http://www.dlr.de/rmc/rm/en

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