World's first lunar exploration rover using FPGA-based RISC-V processor

RISC-V Summit Europe 2026

11 June 2026, 10:00-10:15

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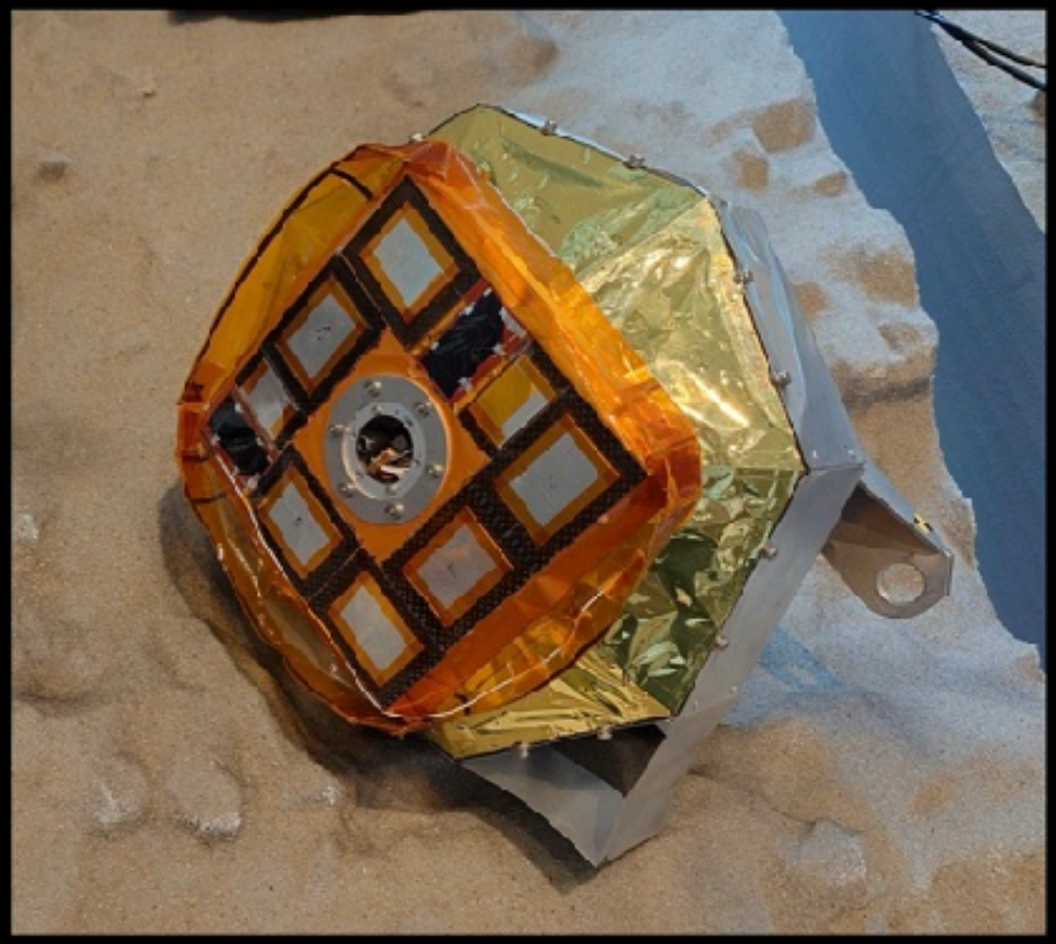
LEV-1 robot onboard SLIM lunar lander



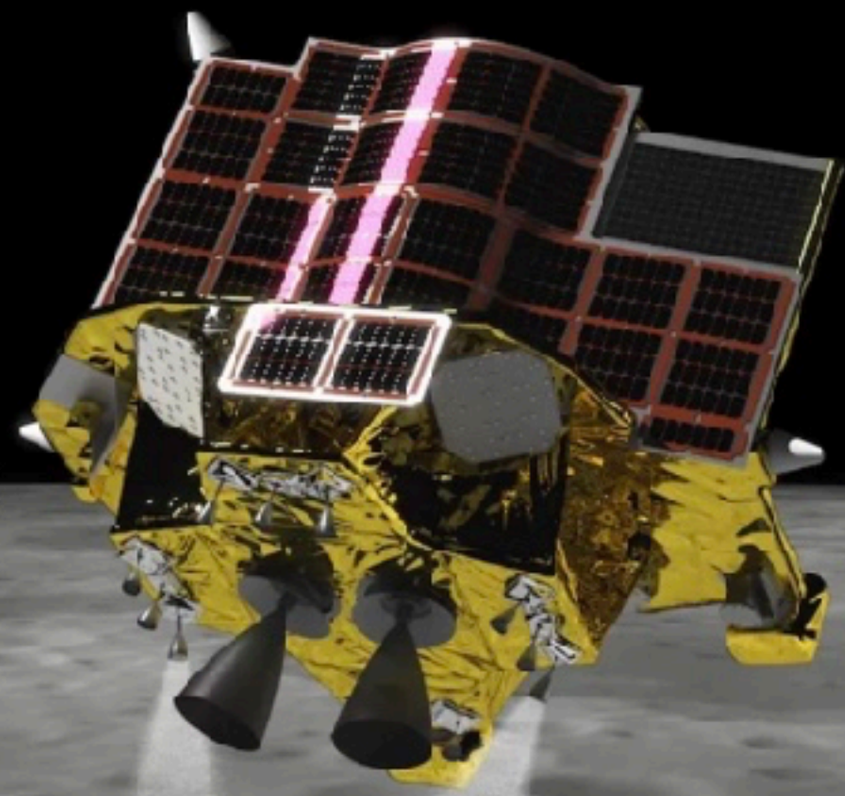
- boarded on SLIM moon lander (launched in Sep 2023, landed in Jan 2024)
- objectives
  - autonomous exploration around the landing area.
  - third-person view imaging of post-landing situation on the Moon
    - transmitting some data from the Moon to Earth, regardless of whether the landing is successful or not, it

SLIM (Moon lander)

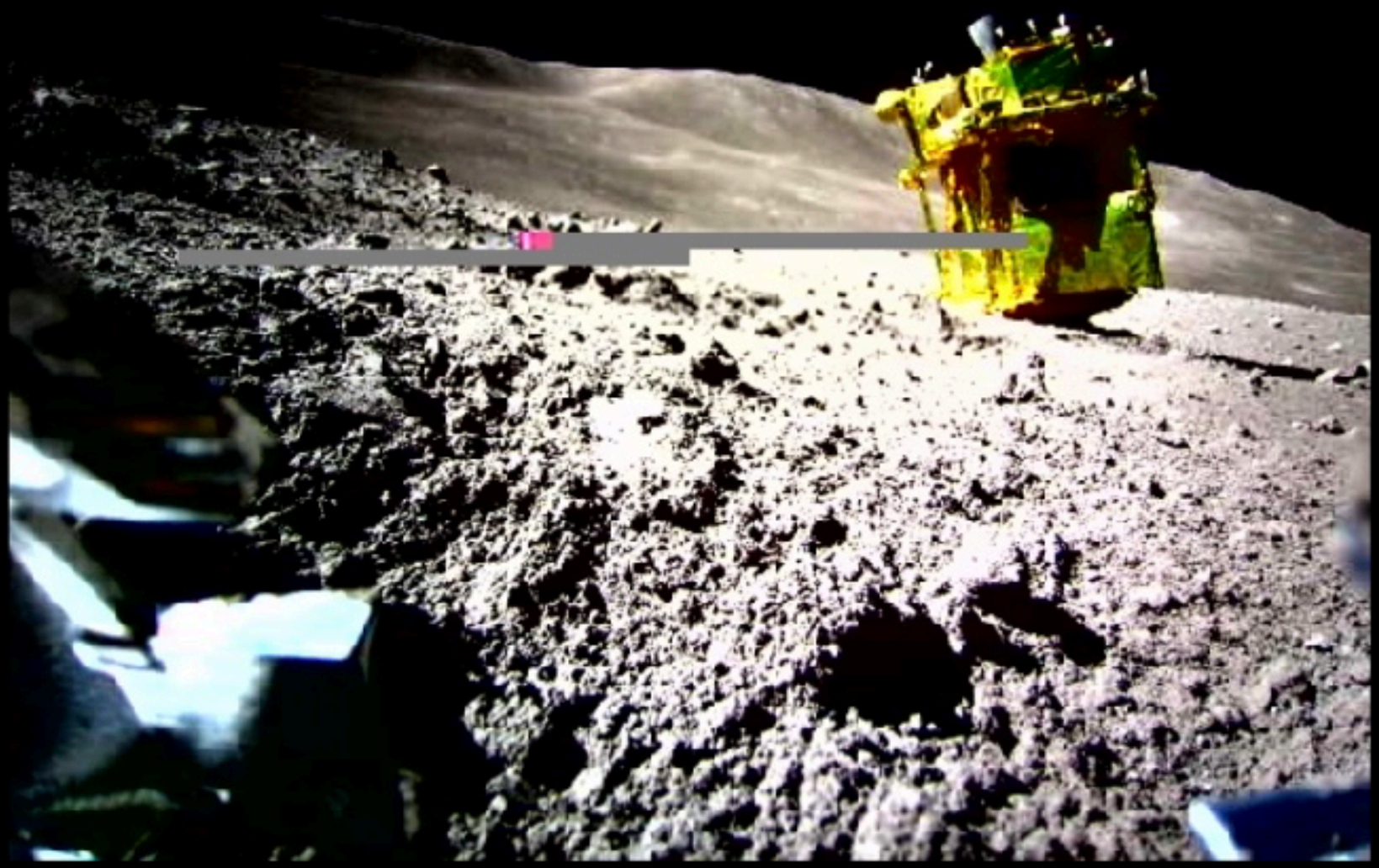
- mass 730kg (wet), 200kg (dry)
- too much focused on precise pin-point landing onto lunar surface
- long-term survival after landing was neglected
- payload < 8[kg]
  - telescopic camera
  - rover system (LEV)

- launched on 06 Sep 2023
- landed on Moon surface on 19 Jan 2024
  - first soft landing mission to the Moon in our country using domestic technologies

- technical challenges by LEV-1
  - hopping mobile system
  - fully autonomous navigation using imagery
  - direct communication to the Earth



Transmitted image from Moon

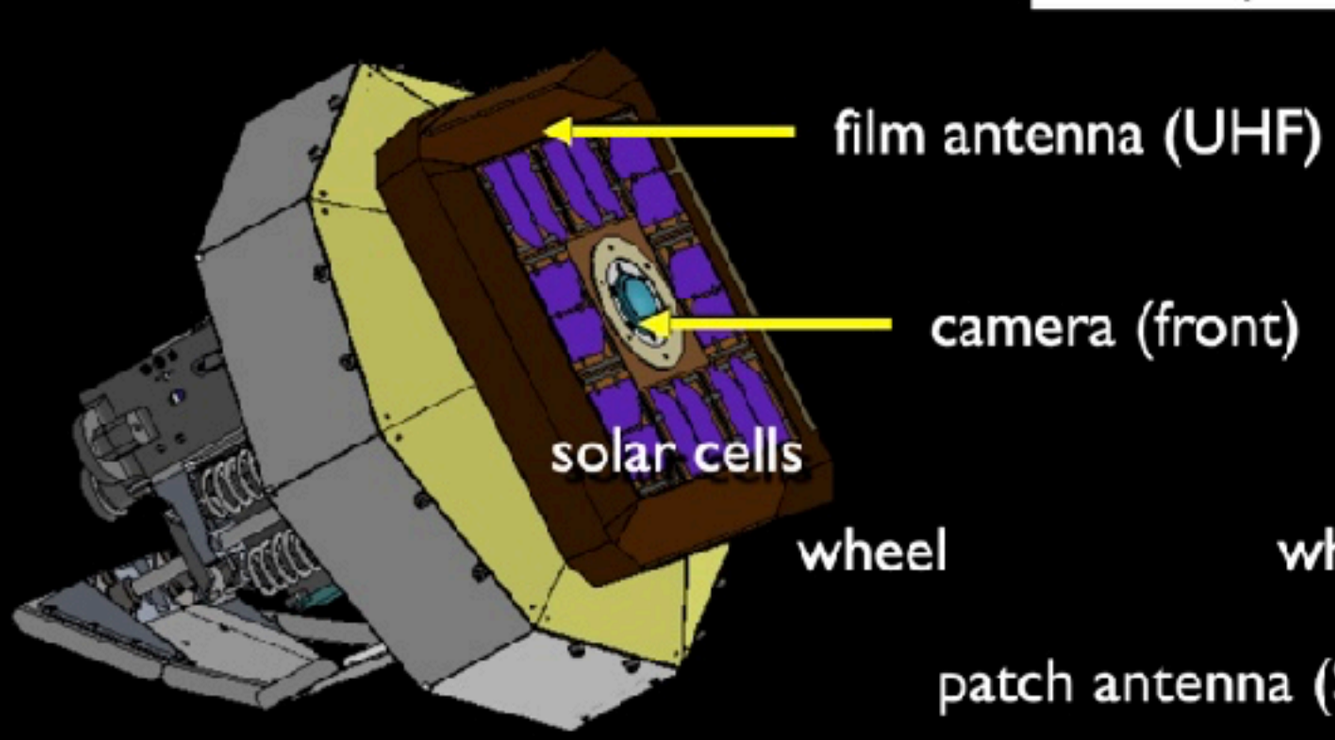


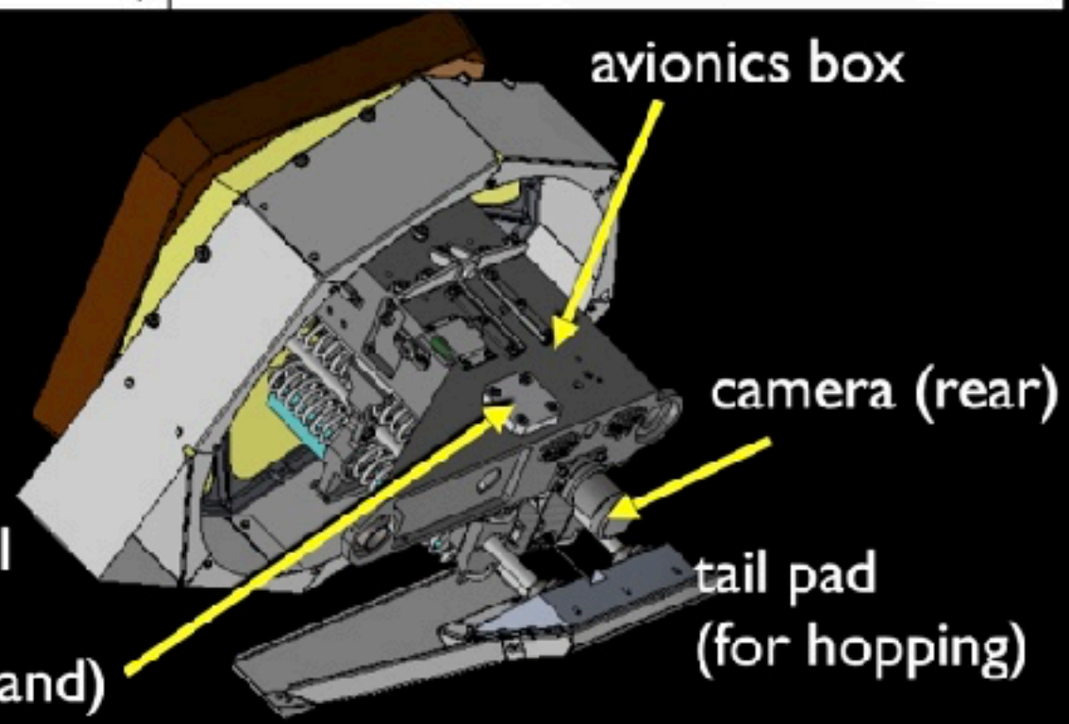
transmitted to the Ground by LEV-1

LEV-1 robot onboard SLIM lunar lander

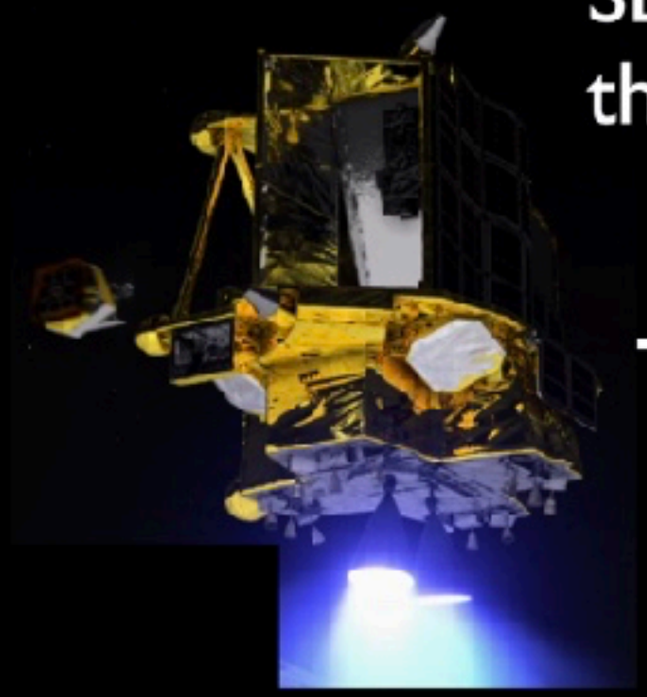
LEV-1 when shipped to SLIM
(with a mounter)

size	wheel diameter ϕ280 mm length 371 mm
mass	2,137 grams
onboard computer	RISC-V on FPGA
mobile system	hopping, wheel (direction control)
communication	S-band(2.2GHz), UHF(430MHz)
power	solar cells (max 4.5W), secondary batteries
sensor (autonomy)	camera x 2, accelerometer, gyro, thermometer, PD
sensor (observation)	radiometer





LEV-1 mission profile



SLIM throws LEV-1 away just before the final landing

Earth

transmission of data directly to the Ground

free fall

landed

hop

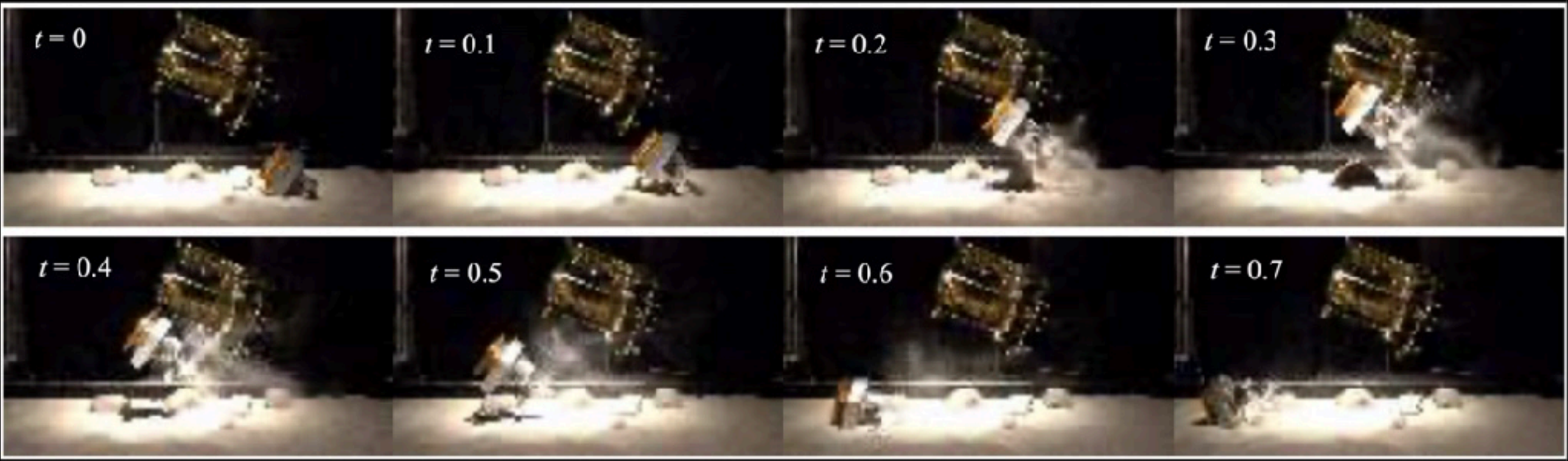
hop

autonomous exploration

SLIM landed

Moon surface

LEV-1 motion (test on the Ground)



hop (approximately one meter on the Ground)

attitude recovery (continuous exploration) and orientation

Mission results

- The Ground stations received the radio and decoded the telemetry from LEV-1 for 109 minutes after the deployment until the temperature of LEV-1 rose above 70 degree C.

- Seven hopping movements were made in 109 minutes.
  - The gravity of the rover changed before and after the hopping actions.

- Purely autonomous. No commanding operation made from the Ground

- Transmitted image disclosed the visual status of SLIM after landed.

- Records
  - first Moon robot in our country
  - World's smallest Moon surface spacecraft communicated with the Ground
  - World's first amateur radio station on the Moon
    - We used amateur radio frequency in UHF

Capabilities of onboard computer

Device control IP in FPGA

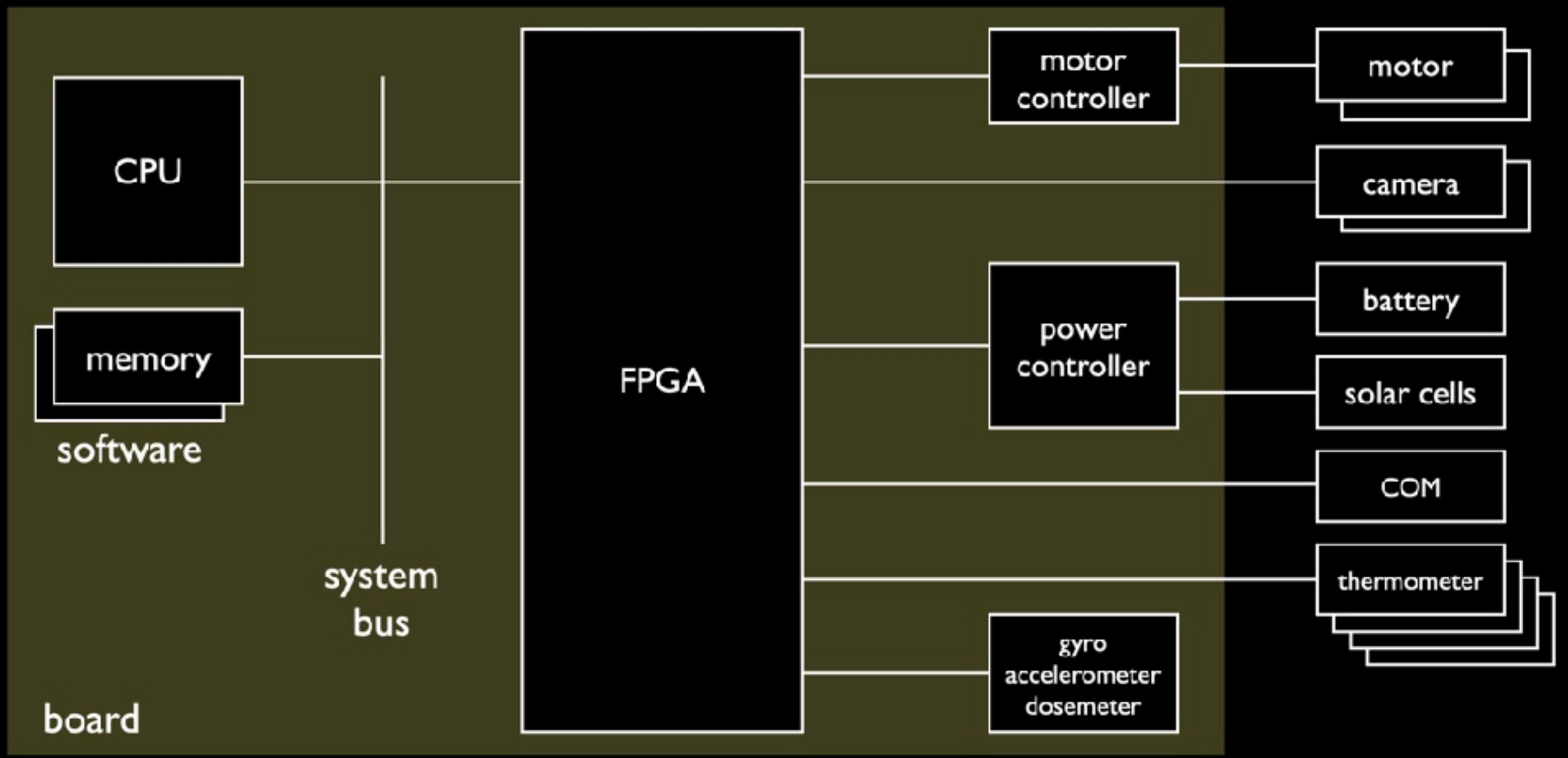
- motor controller (2ch: hop and turn)
- communication module
- power controller (secondary battery, solar cells)
- sensors
  - camera (2ch)
  - thermometer (4ch)
- sensors (on board)
  - gyro
  - accelerometer
  - dosemeter

Software (works in realtime OS implemented in RISC-V core)

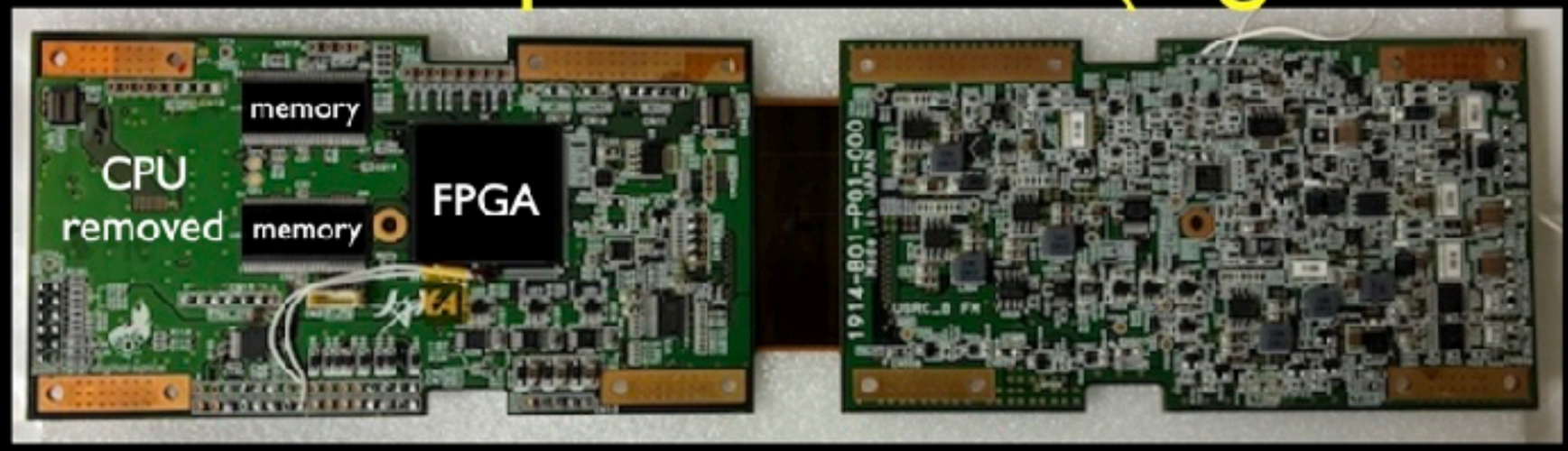
- stored in memory
- realtime OS (iTron) tasks work
  - device control mentioned in above
  - autonomous control

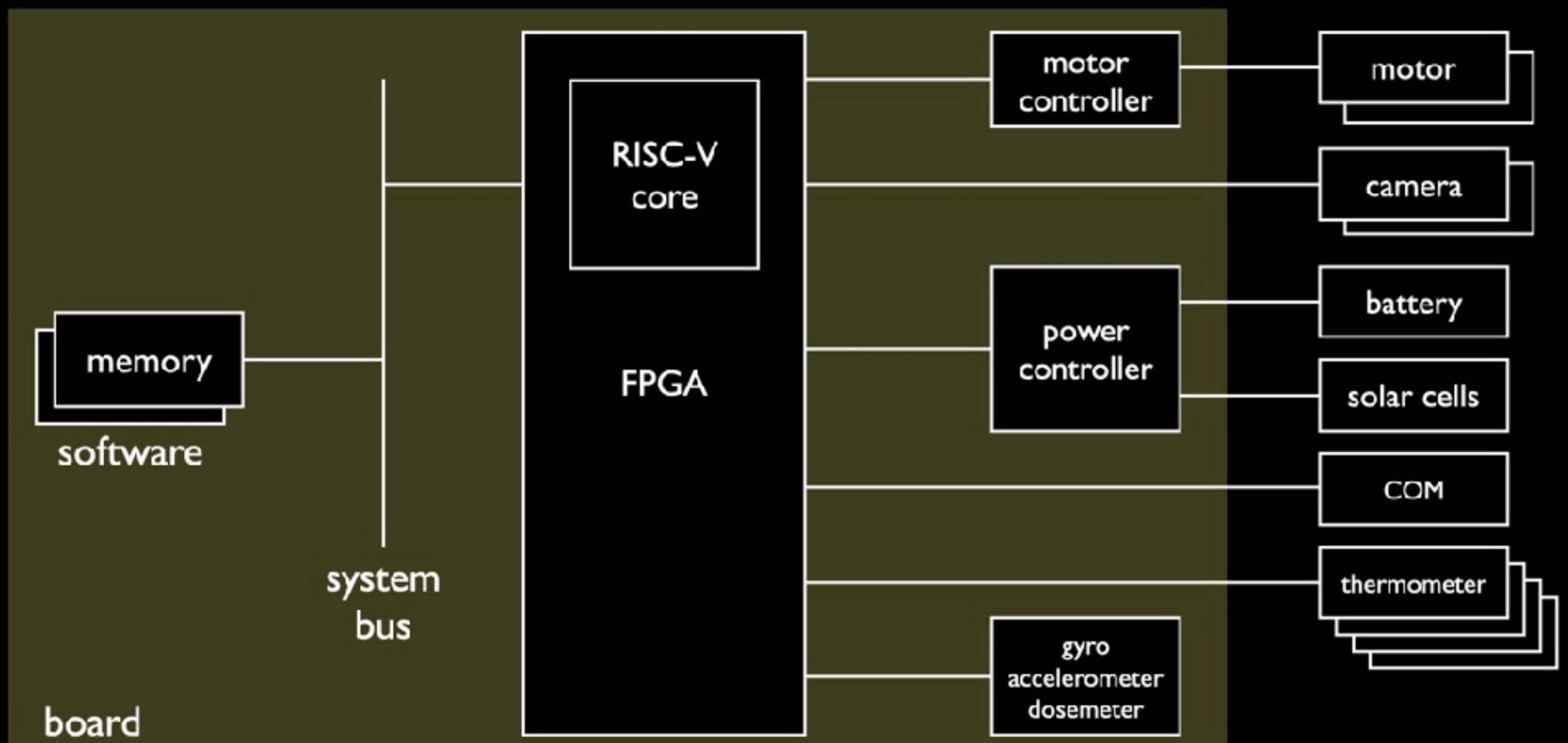
Onboard computer board (initial)

Initial version of LEV-1 onboard computer board (used for radiation tolerance test)

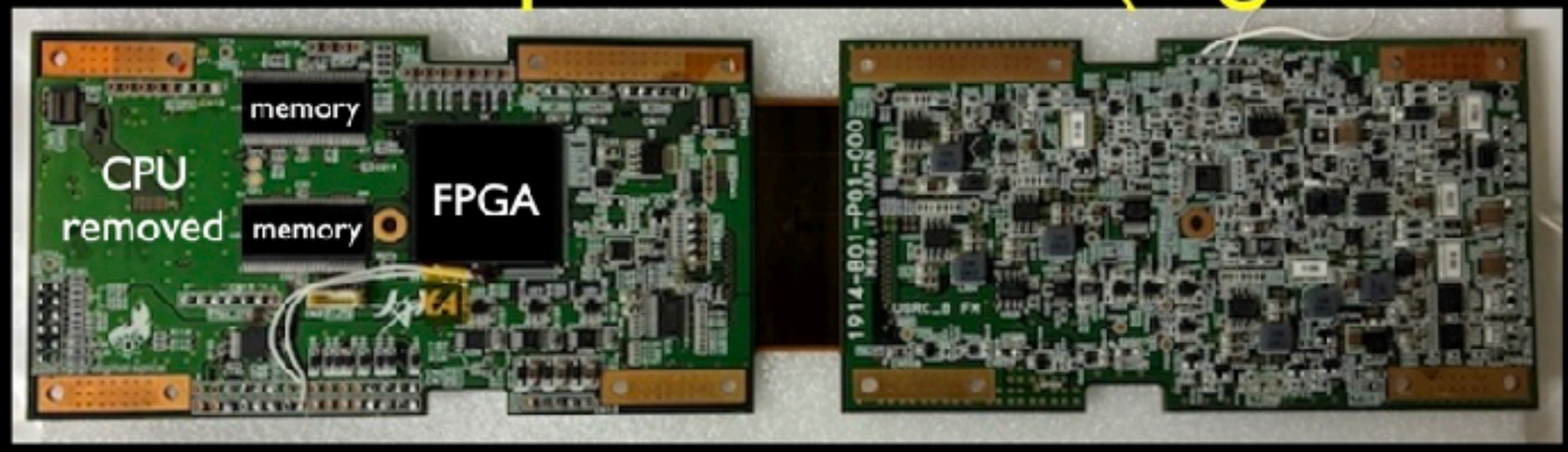


Onboard computer board (flight model)





Onboard computer board (flight model)

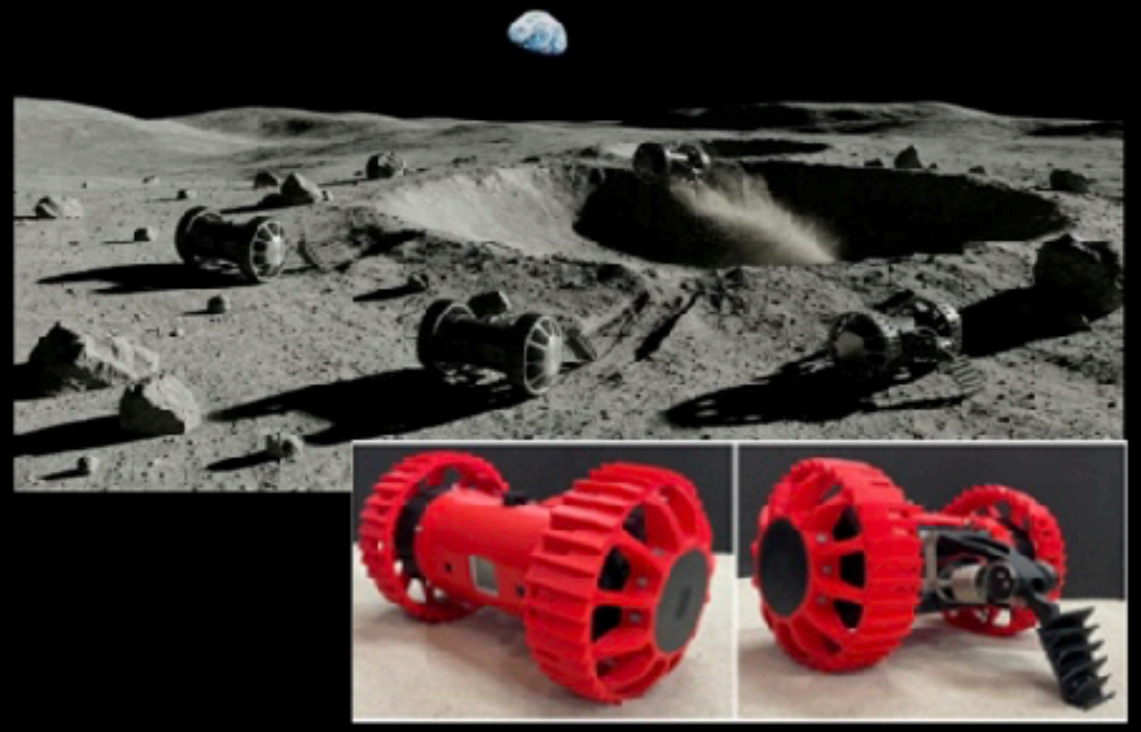


- Software developed for CPU can be used for RISC-V
  - compatibility in source codes

- The developed onboard computer retains both merits by FPGA and CPU

- FPGA
  - low power consumption
  - high reliability for the use in space
- software woking in CPU
  - robot software is complicated with many tasks concurrently working.
  - software-based development makes debugging easy and highly reliable

New version



exploration by small swarm rovers

- developed for small swarm rovers under governmental fund
- No CPUs, one FPGA
- currently three RISC-V cores implemented in one FPGA
- Realtime OS (iTron) works in RISC-V cores
  - Tasks can be dynamically reassigned in different cores
  - Tasks in different cores can synchronise

End

Thank you for your attention