Application of planar air-bearing microgravity simulator for experiments related to ADR missions

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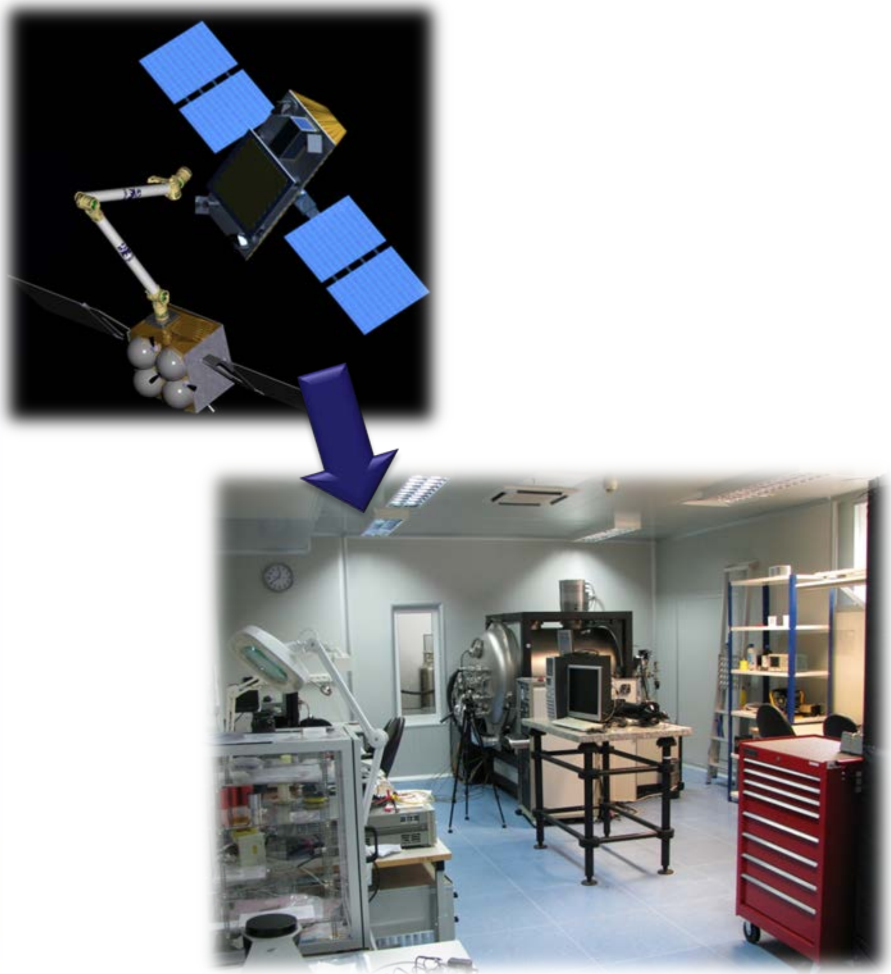
Outline

1. Introduction.
2. Planar air-bearing microgravity simulator.
3. Experiments on planar air-bearing microgravity simulator related to ADR missions.
4. Planned experiments (e.deorbit Phase B1) and test facility upgrades.
5. Summary.

Tests of robotic systems for planned ADR missions



Orbital capture manoeuvre with a manipulator (artist concept) and laboratory at CBK PAN.

- Complicated robotic systems required for planned ADR missions must be tested in the laboratory conditions.
- Microgravity is the aspect of space environment that is especially hard to be recreated on Earth.
- Microgravity test-bed is required for tests of hardware (e.g., manipulators), tests of control algorithms and for validation of dynamical models and numerical simulations.

Simulations of microgravity conditions

- How we can simulate microgravity conditions on Earth?
- Various possibilities:
  - weight-reducing suspension systems,
  - systems based on industrial robots (e.g., EPOS),
  - underwater tests with neutral buoyancy vehicles,
  - parabolic flights,
  - air-bearing test-beds.

Air-bearing test-bed at CBK PAN.

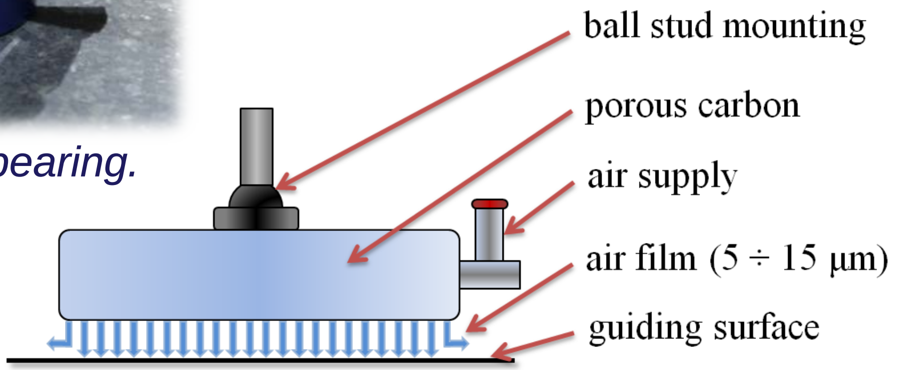
Weight-reducing suspension system at CBK PAN.

Planar air-bearing microgravity simulator 1/2

- Tested objects (e.g., satellite mock-up, manipulator) are mounted on planar air-bearings.
- Air-bearings provide an exceedingly low friction (friction coefficient around 10^{-5}) and allow almost frictionless motion on the table surface.

Satellite mock-up.

Planar air-bearing.



Schematic view of an air-bearing.

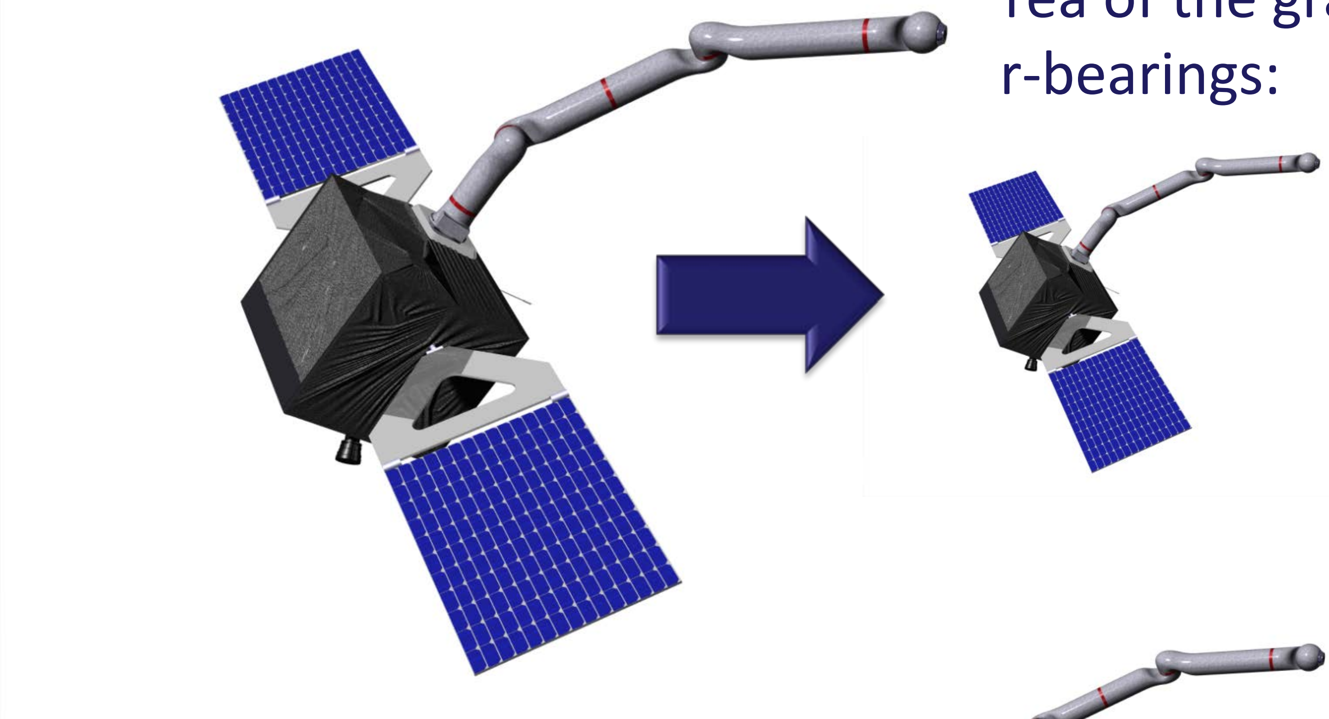
Planar air-bearing microgravity simulators 2/2

Advantages	Disadvantages
• Small disturbances: Residual gravity acceleration is around $10^{-3} \div 10^{-5}$ g. • Relatively long time of experiment: at least several minutes. • Low costs of operations. • Many possible applications (not only in the field of space robotics).	• Motion limited to one plane only (simulation of microgravity conditions in two dimensions). • Limited size of the experimental area. • Tested systems must usually be scaled down. • Precise calibration required for free-floating experiments.

Scaling

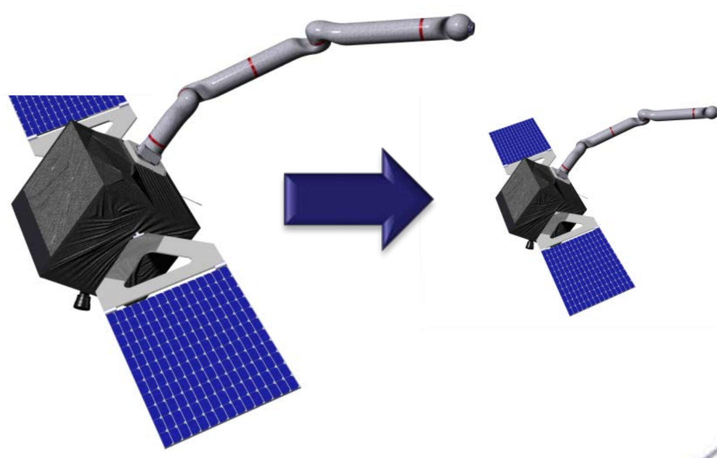
Object… …rea of the granite table a… …r-bearings:

where: … the scaled value, … exponent.



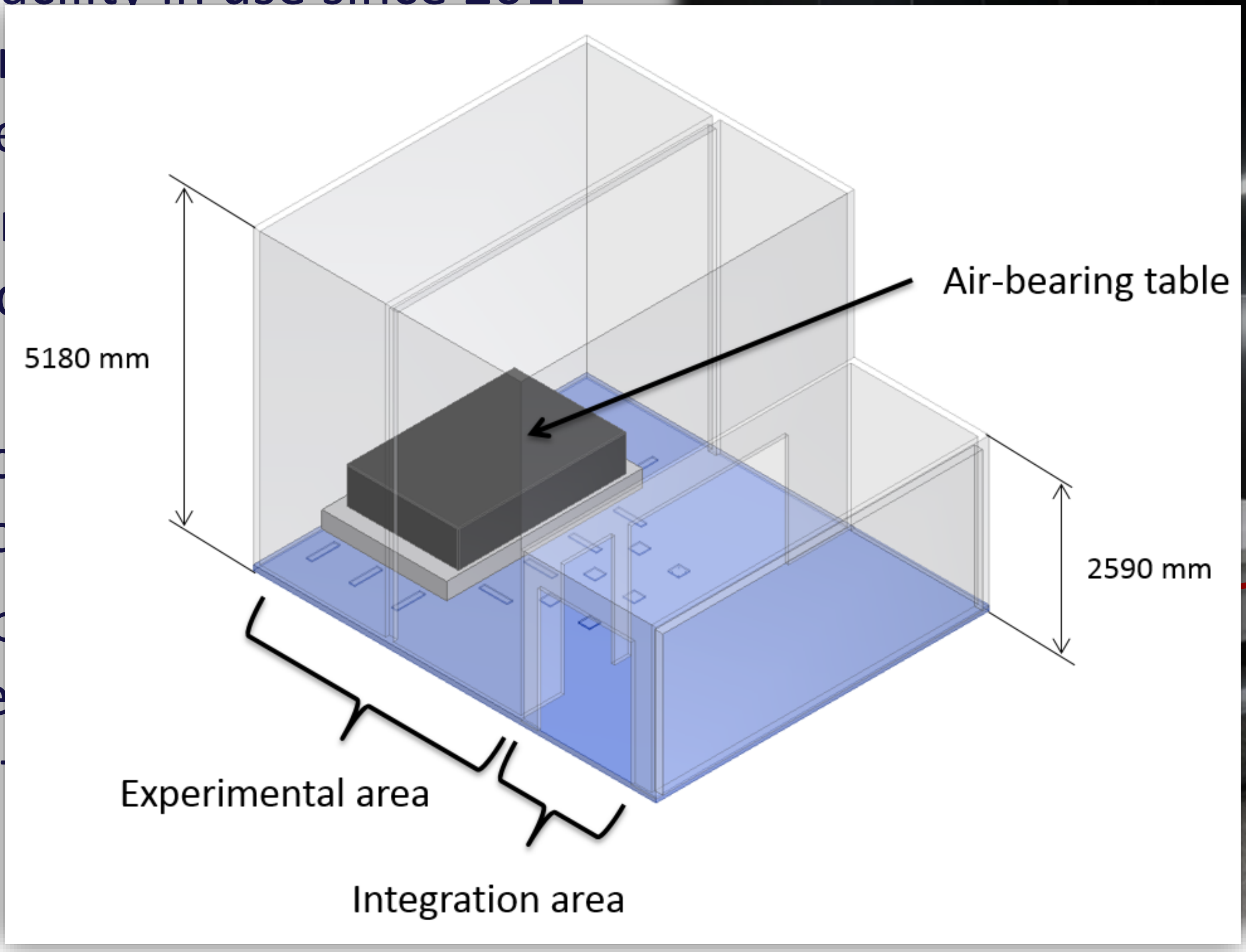
Scalin…

1		
2	Mass	3
3	Inertia	5
4	Velocity	0
5	Acceleration	-1



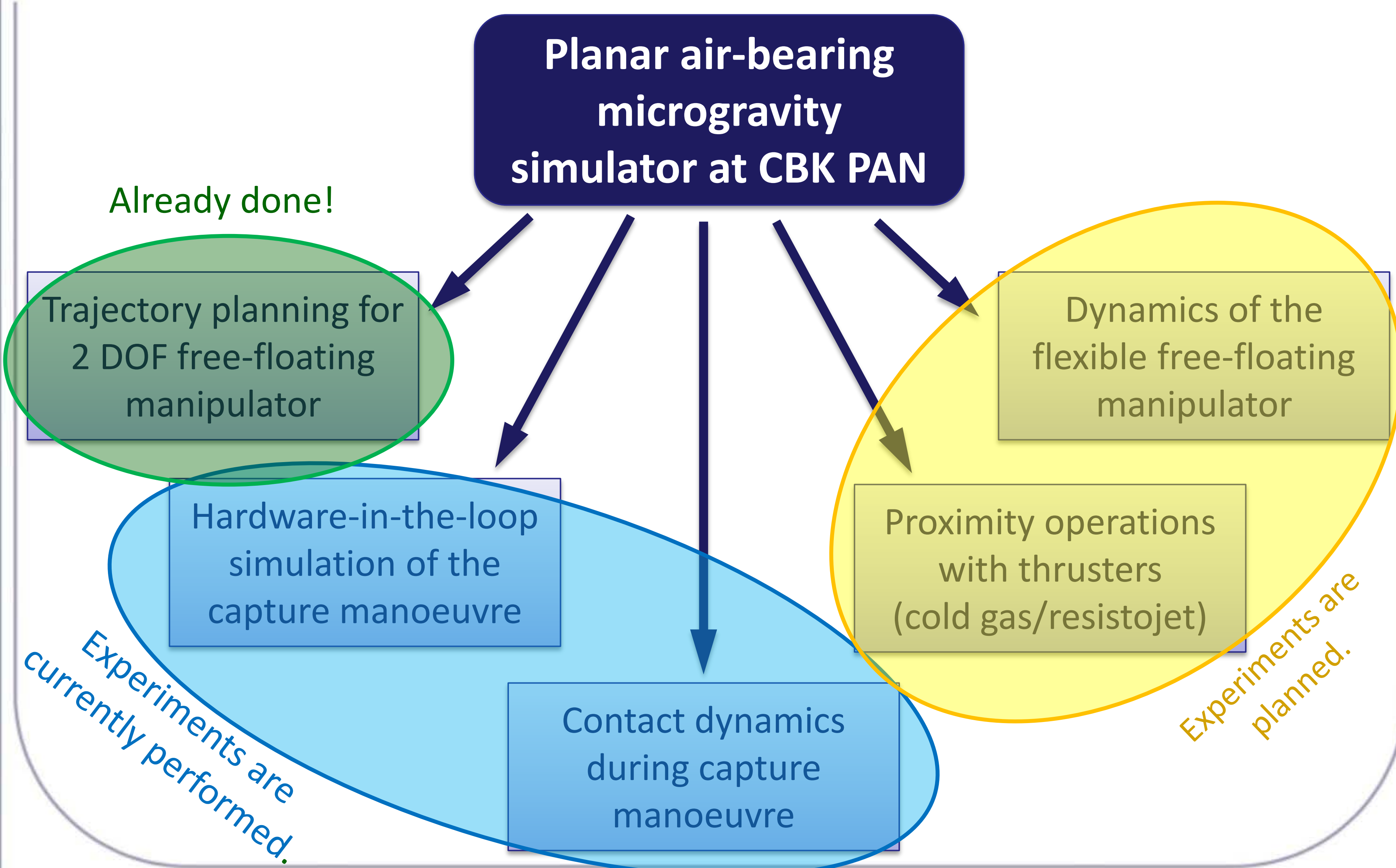
Air-bearing microgravity simulator at CBK PAN

- Test facility in use since 2012 (first pr confere
- Major the enc
- Used connec robotic
- Test-b granite above t

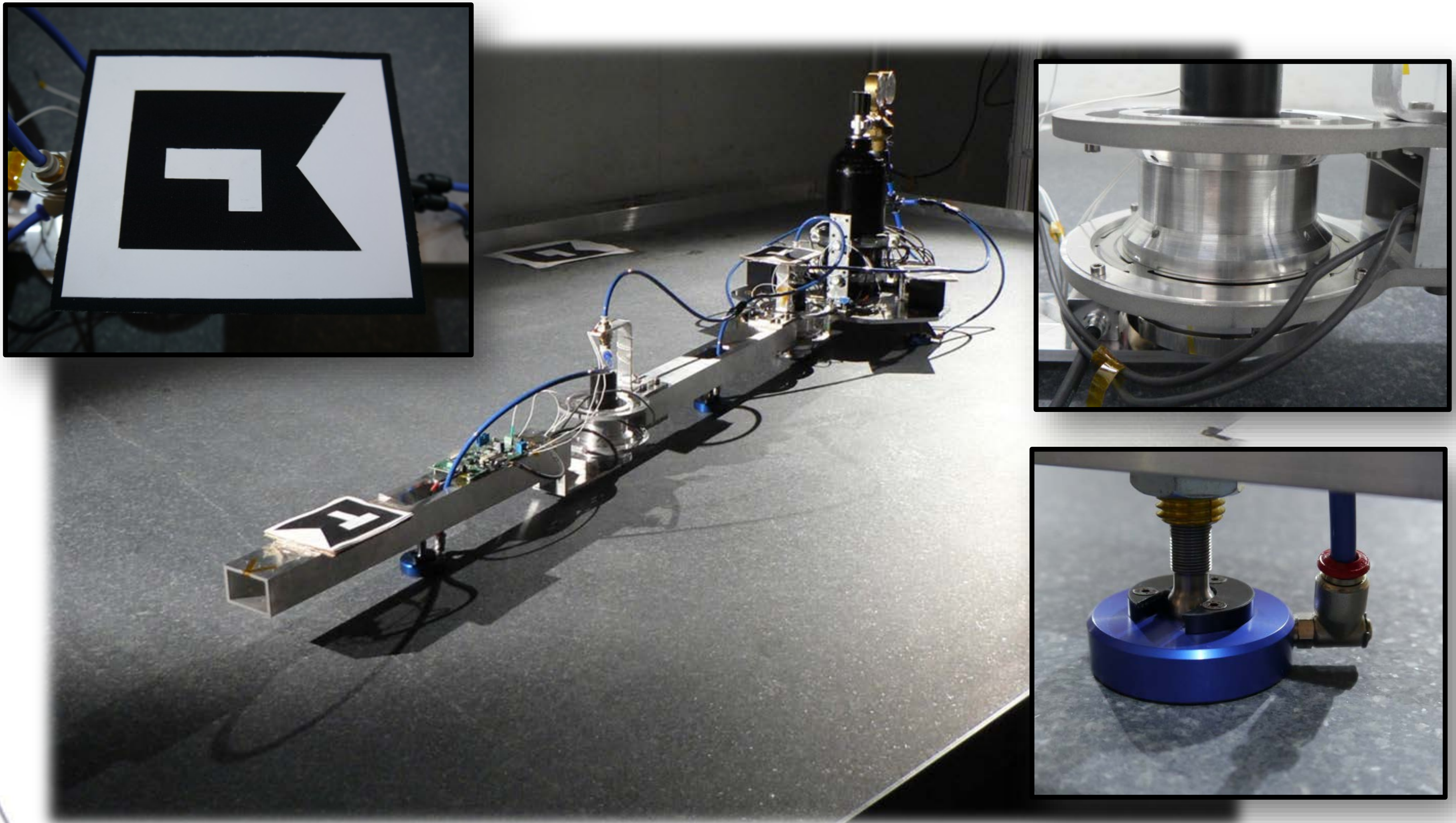


Granite table at CBK PAN.

Experiments related to ADR missions

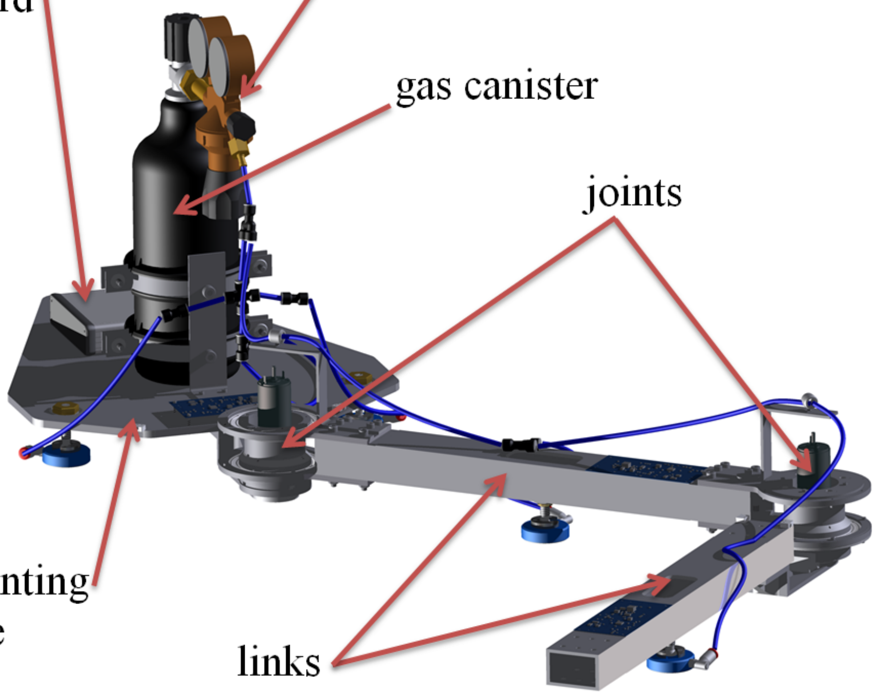


Satellite-manipulator mock-up 1/2



Satellite-manipulator mock-up.

Satellite-manipulator mock-up 2/2

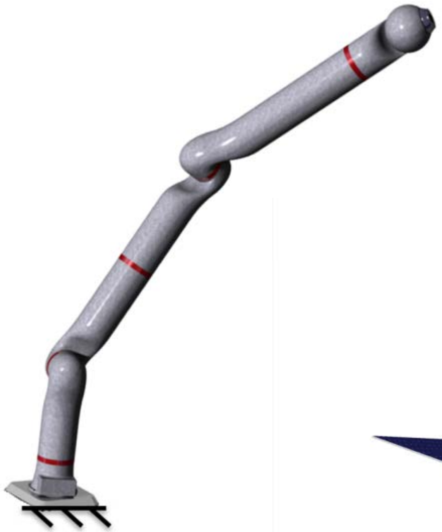


Schematic view of the planar satellite-manipulator system.

Geometrical and mass properties of the planar satellite-manipulator system.

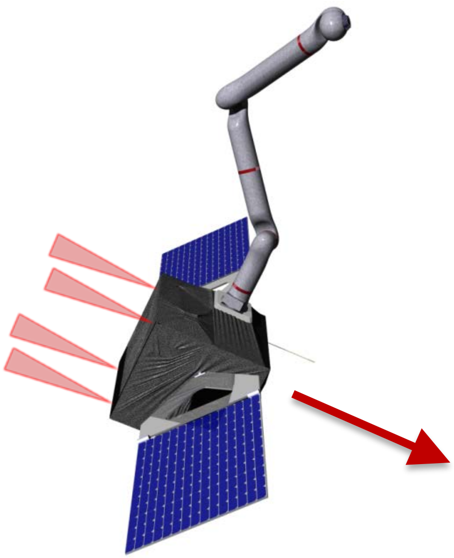
	Parameter	Value
1	Satellite mass	12.9 kg
2	Satellite moment of inertia	0.208 kg·m^2
3	Link 1 mass	4.5 kg
4	Link 1 moment of inertia	0.32 kg·m^2
5	Link 1 length	0.619 m
6	Link 2 mass	1.5 kg
7	Link 2 moment of inertia	0.049 kg·m^2
8	Link 2 length	0.6 m

Fixed-base, free-floating and free-flying manipulators



Fixed-base manipulator.

Free-floating manipulator.



Free-flying manipulator.

Satellite-manipulator dynamics

Equation of satellite-manipulator dynamics:

$$\underbrace{\mathbf{M}(\mathbf{q}_p)\ddot{\mathbf{q}}_p}_{\text{Mass matrix}} + \underbrace{\mathbf{C}(\mathbf{q}_p, \dot{\mathbf{q}}_p)\dot{\mathbf{q}}_p}_{\text{Coriolis matrix}} + \underbrace{\mathbf{G}(\mathbf{q}_p)}_{\text{Potential forces}} = \underbrace{\mathbf{Q}}_{\text{Torques}}$$

Ordinary manipulators (fixed-base, working on Earth)	Space manipulators (free-floating and free-flying)
$\mathbf{q}_p = [\theta_1, \theta_2, \dots, \theta_n]^T$	$\mathbf{q}_p = [\mathbf{r}_s \quad \mathbf{\Theta}_s \quad \theta_1 \quad \theta_2 \quad \dots \quad \theta_n]^T$
$\mathbf{G}(\mathbf{q}_p) \neq [0]$	$\mathbf{G}(\mathbf{q}_p) \approx [0]$

Inverse dynamics problem

Trajectory of the manipulator end-effector is defined in the velocity space.

$$\dot{\boldsymbol{\theta}} = (\mathbf{J}_M - \mathbf{J}_S\mathbf{H}_2^{-1}\mathbf{H}_3)^{-1}\left(\begin{bmatrix}\mathbf{v}_{ee}\\ \boldsymbol{\omega}_{ee}\end{bmatrix} - \mathbf{J}_S\mathbf{H}_2^{-1}\begin{bmatrix}\mathbf{f}_m\\ \mathbf{f}_{am}\end{bmatrix}\right)$$

$$\begin{bmatrix}\mathbf{f}_m\\ \mathbf{f}_{am}\end{bmatrix} = \begin{bmatrix}\int \mathbf{F}_s dt\\ \int \mathbf{H}_s + \tilde{\mathbf{r}}_s\mathbf{F}_s dt\end{bmatrix}$$

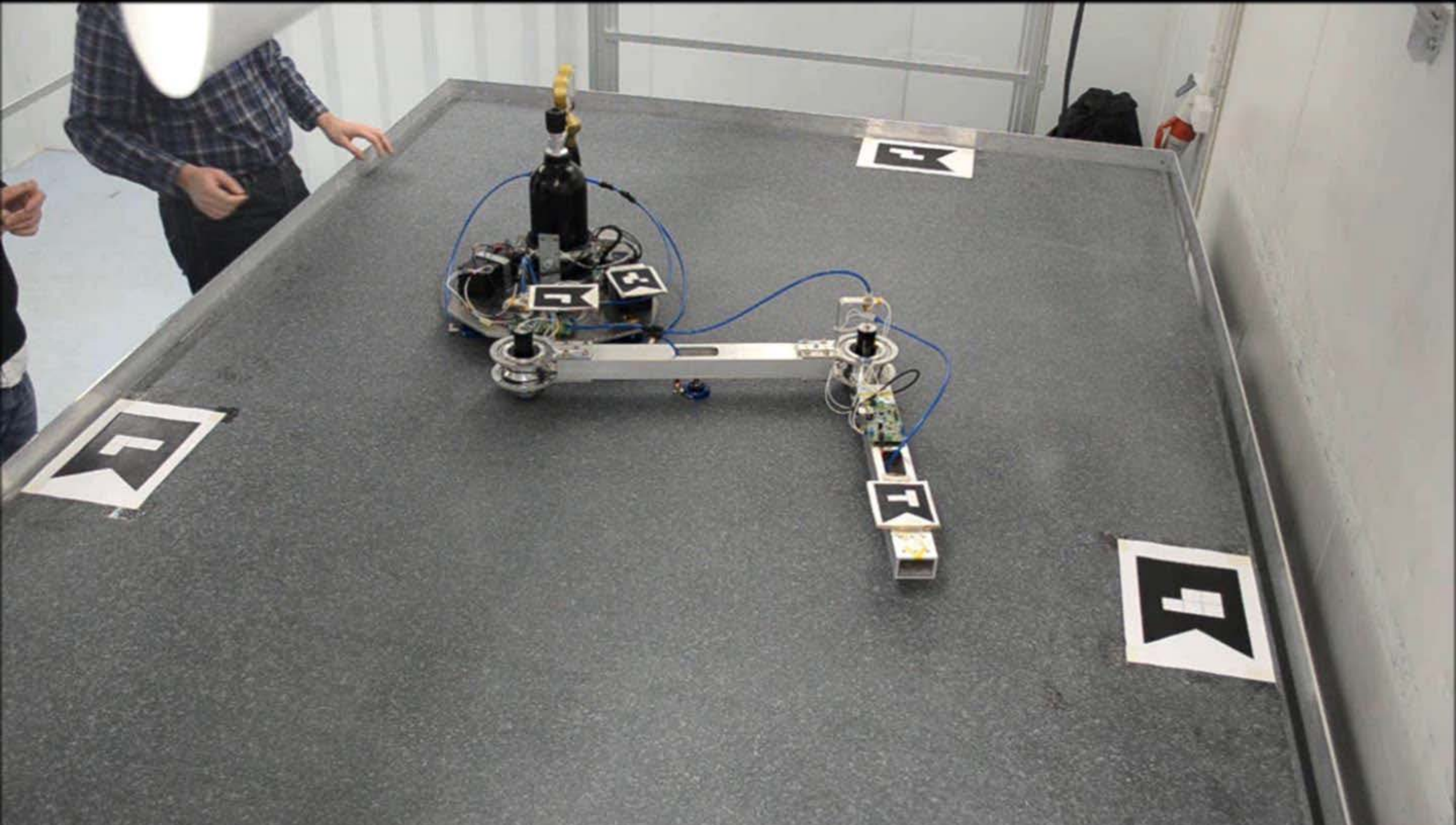
$$\begin{bmatrix}\mathbf{v}_s\\ \boldsymbol{\omega}_s\end{bmatrix} = \mathbf{H}_2^{-1}\left(\begin{bmatrix}\mathbf{f}_m\\ \mathbf{f}_{am}\end{bmatrix} - \mathbf{H}_3\dot{\boldsymbol{\theta}}\right)$$

Matrices $\mathbf{H}_2$ i $\mathbf{H}_3$ are influenced not only by the state of the manipulator, but also by the state of the servicing satellite.

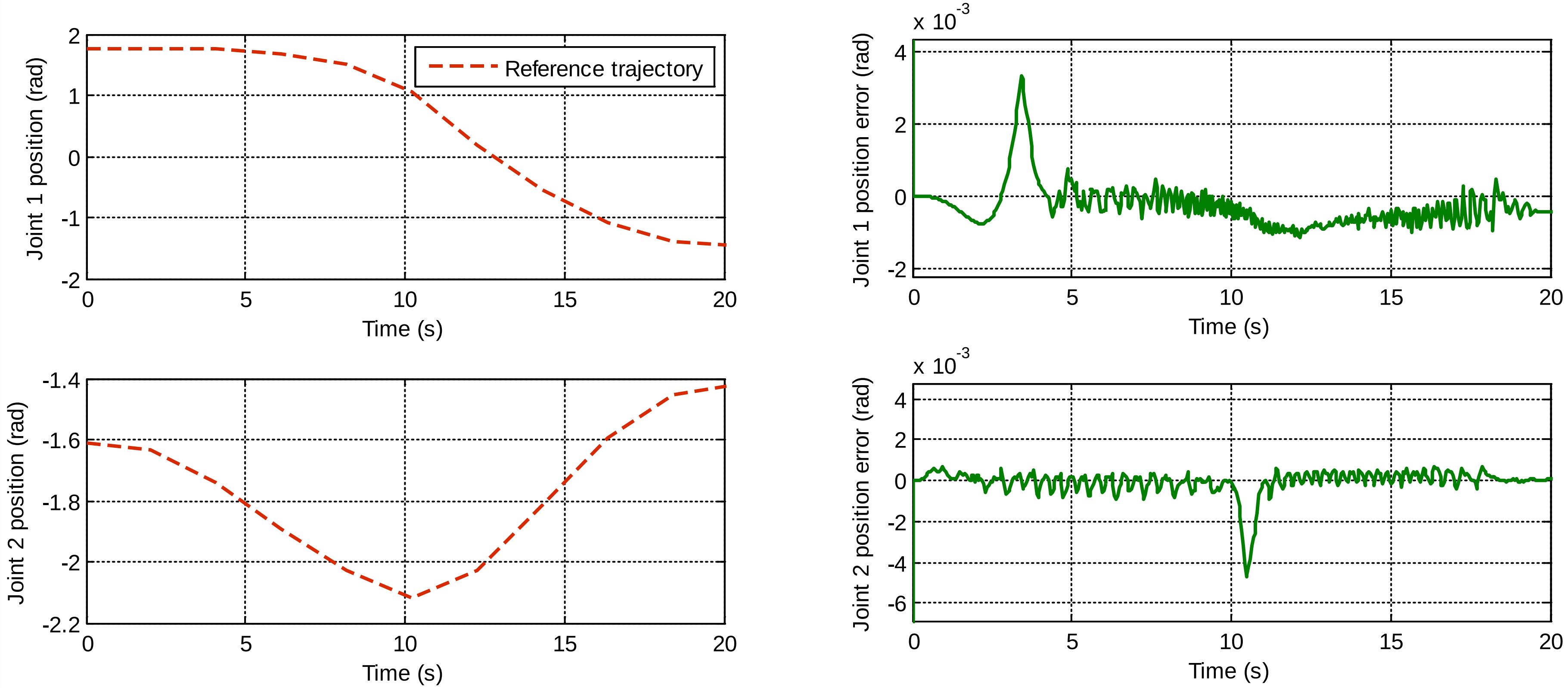
$$\mathbf{J}_s = \begin{bmatrix}\mathbf{I} & \tilde{\mathbf{r}}_{ee\_s}^T\\ 0 & \mathbf{I}\end{bmatrix} \qquad \mathbf{J}_M = \begin{bmatrix}\mathbf{k}_1 \times (\mathbf{r}_{ee} - \mathrm{r}_1) & \dots & \mathbf{k}_n \times (\mathbf{r}_{ee} - \boldsymbol{r}_n)\\ \mathbf{k}_1 & \dots & \mathbf{k}_n\end{bmatrix}$$

Joint control torques **Q** are computed for manipulator trajectory obtained in the joint space:

$$\mathbf{Q} = \mathbf{M}(\mathbf{q}_p)\ddot{\mathbf{q}}_p + \mathbf{C}(\mathbf{q}_p, \dot{\mathbf{q}}_p)\dot{\mathbf{q}}_p \qquad \mathbf{Q} = [\mathbf{F}_s \quad \mathbf{H}_s \quad \mathbf{u}]^T$$



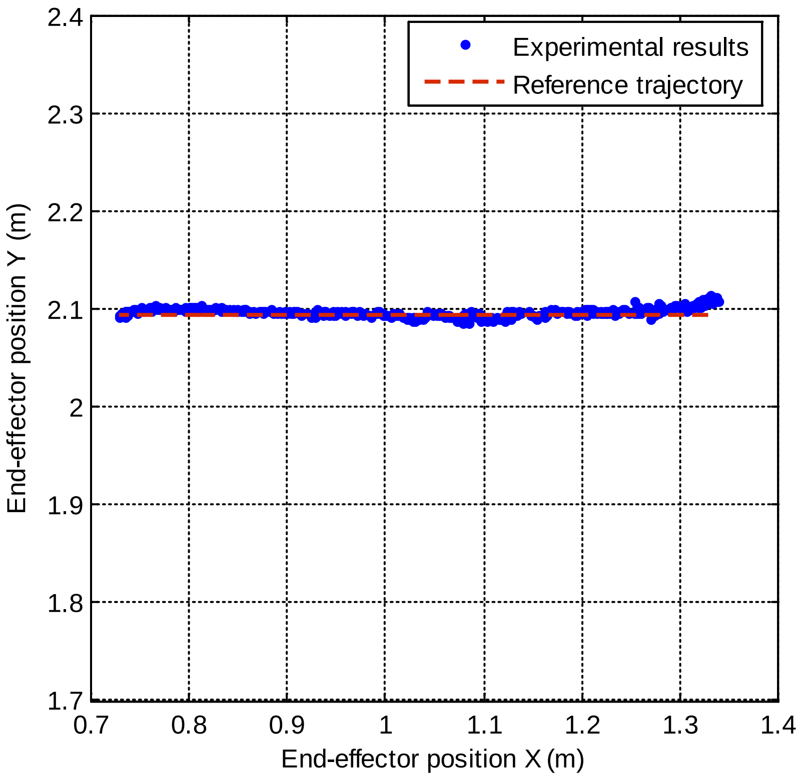
Air-bearing table: straight line trajectory 1/2



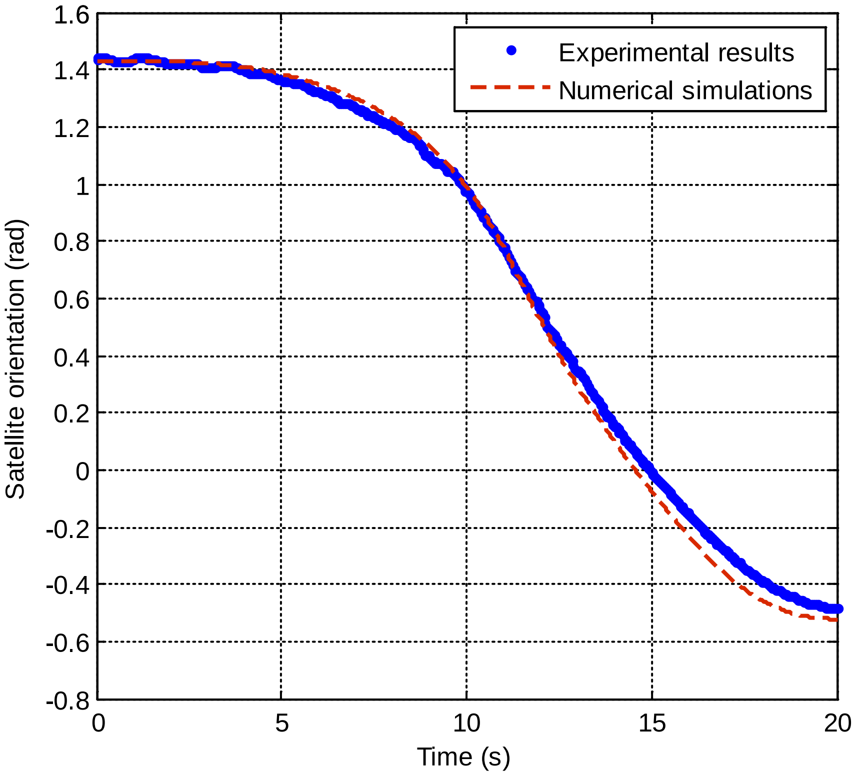
Reference positions of manipulator joints calculated for the end-effector reference trajectory.

Error of manipulator joints positions (difference between the reference trajectory and data obtained from encoders).

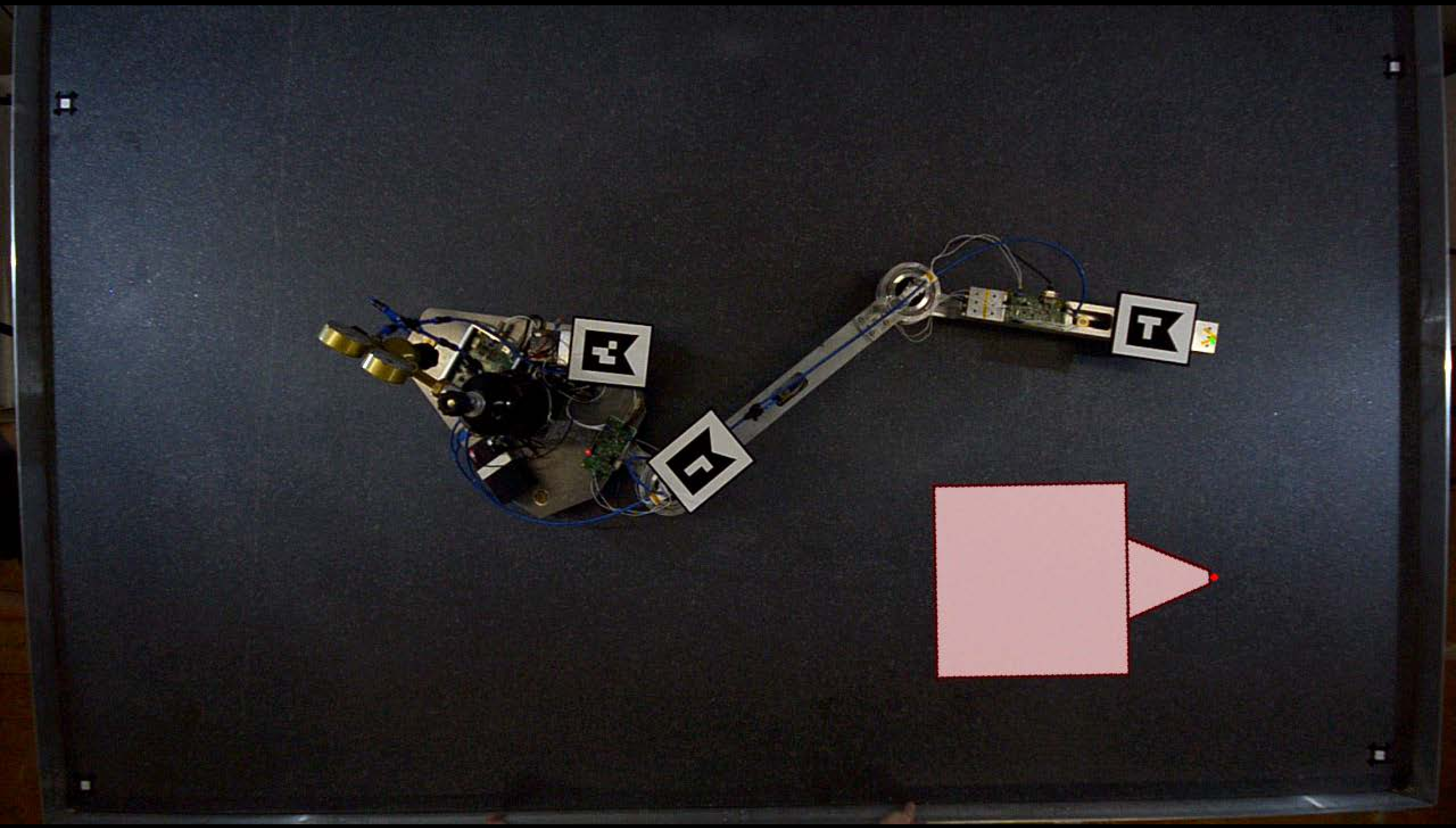
Air-bearing table: straight line trajectory 2/2



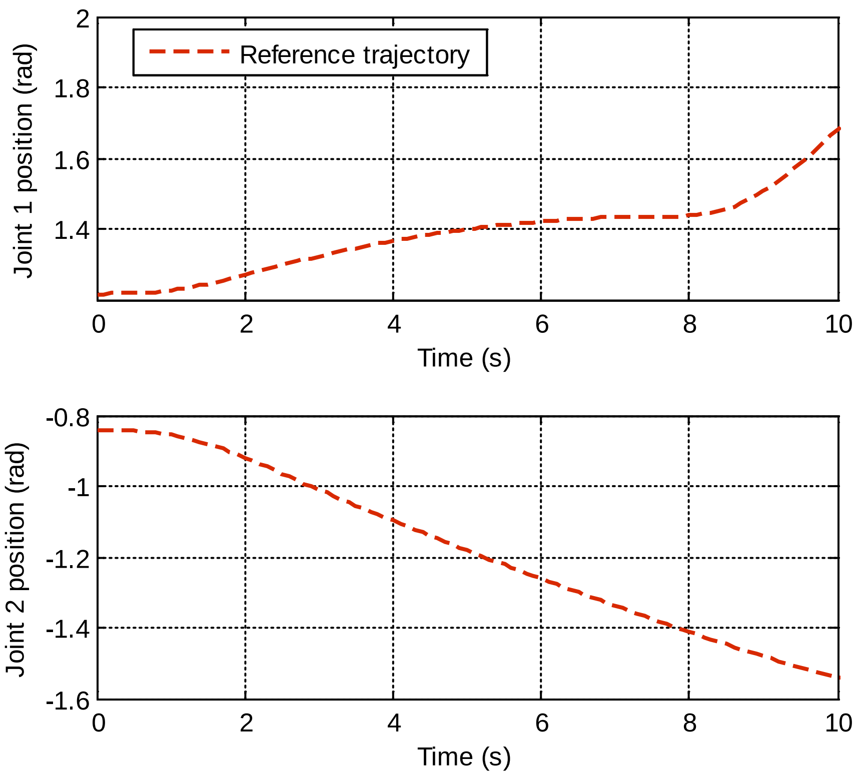
Comparison between the reference end-effector trajectory and end-effector position measured during the experiment.



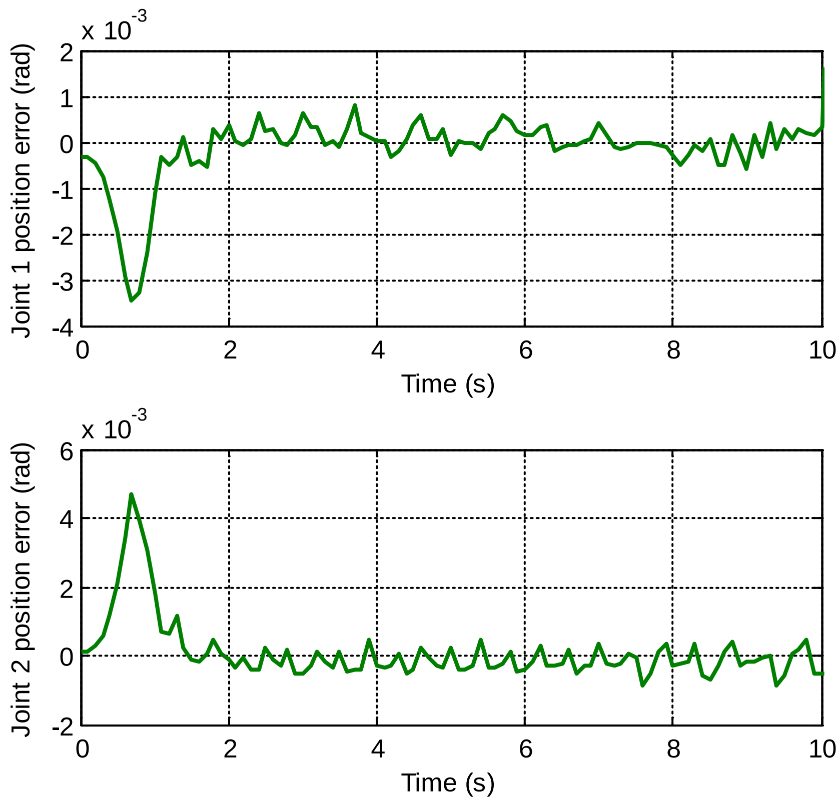
Comparison between the satellite orientation obtained from numerical simulations and orientation of manipulator base measured during the experiment.



Air-bearing table: capture trajectory 1/2

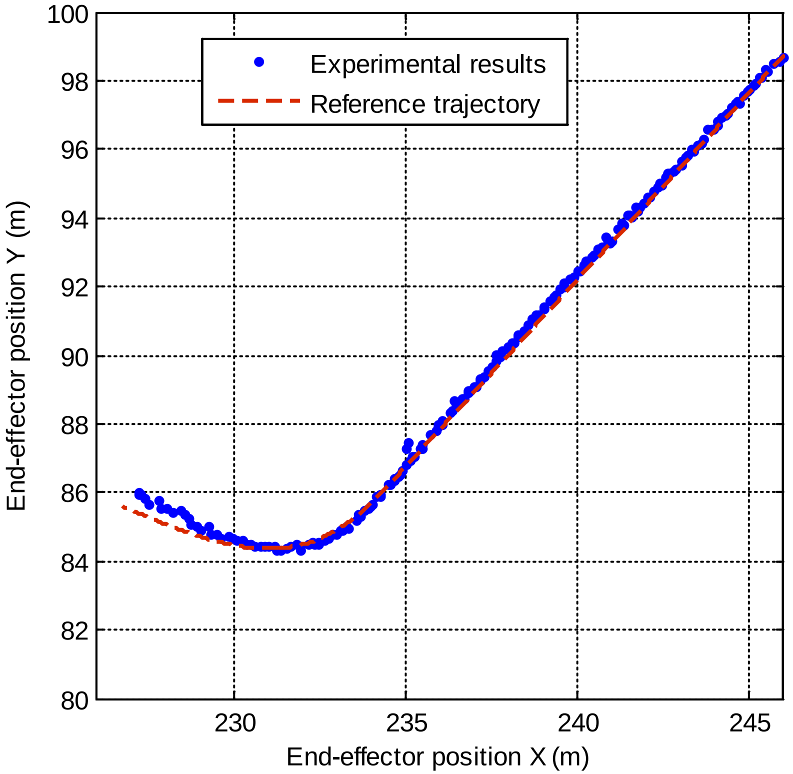


Reference positions of manipulator joints calculated for the end-effector reference trajectory.

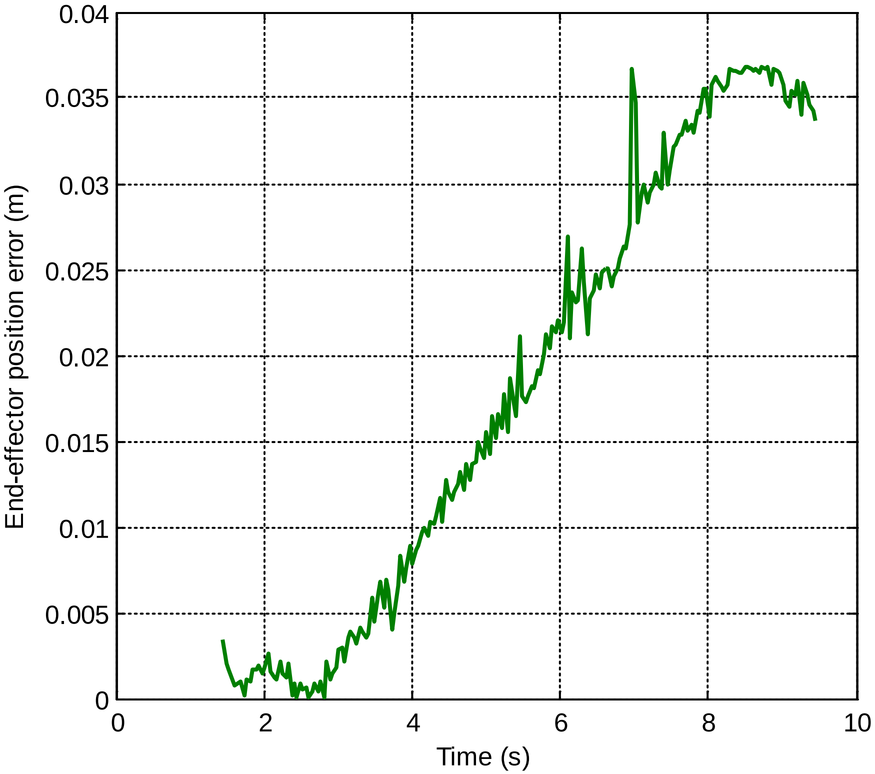


Error of manipulator joints positions (difference between the reference trajectory and data obtained from encoders).

Air-bearing table: capture trajectory 2/2



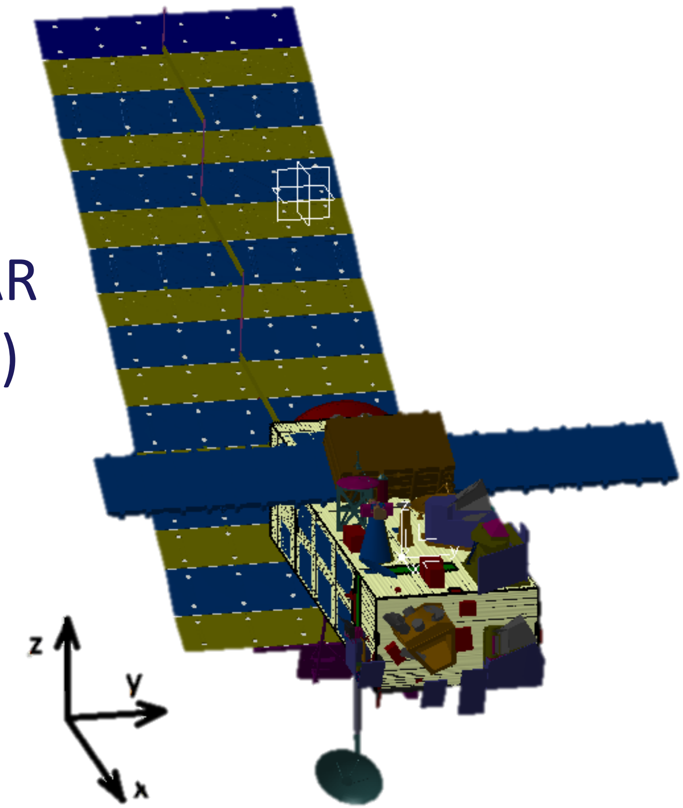
Comparison between the reference end-effector trajectory and end-effector position measured during the experiment.



End-effector position error (difference between the reference trajectory and position measured during the experiment).

Experiments in the frame of e.deorbit project 1/5

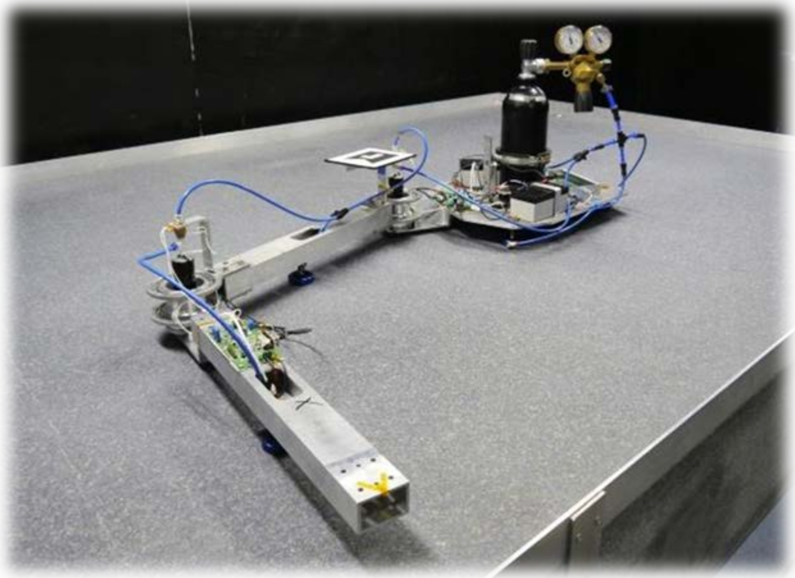
- Simulation of the capture manoeuvre with scaled down mock-up of chaser, gripper, manipulator, target and LAR.
- During experiment the robotic arm will move the gripper mock-up towards the LAR mock-up (mounted on the target platform) and gripper jaws will close on LAR.
- Experiment limited to one plane (misalignments between the gripper and LAR in the plane parallel to the table surface).



Simplified Envisat model.

Experiments in the frame of e.deorbit project 2/5

- Main objectives:
  1. To experimentally investigate contact forces and torques between the gripper and the LAR.
  2. To experimentally investigate dynamic impact of contact phenomena on chaser during the capture manoeuvre.
  3. To assess the possibility of using planar air-bearing microgravity simulator to obtain valuable data during development of ADR missions.



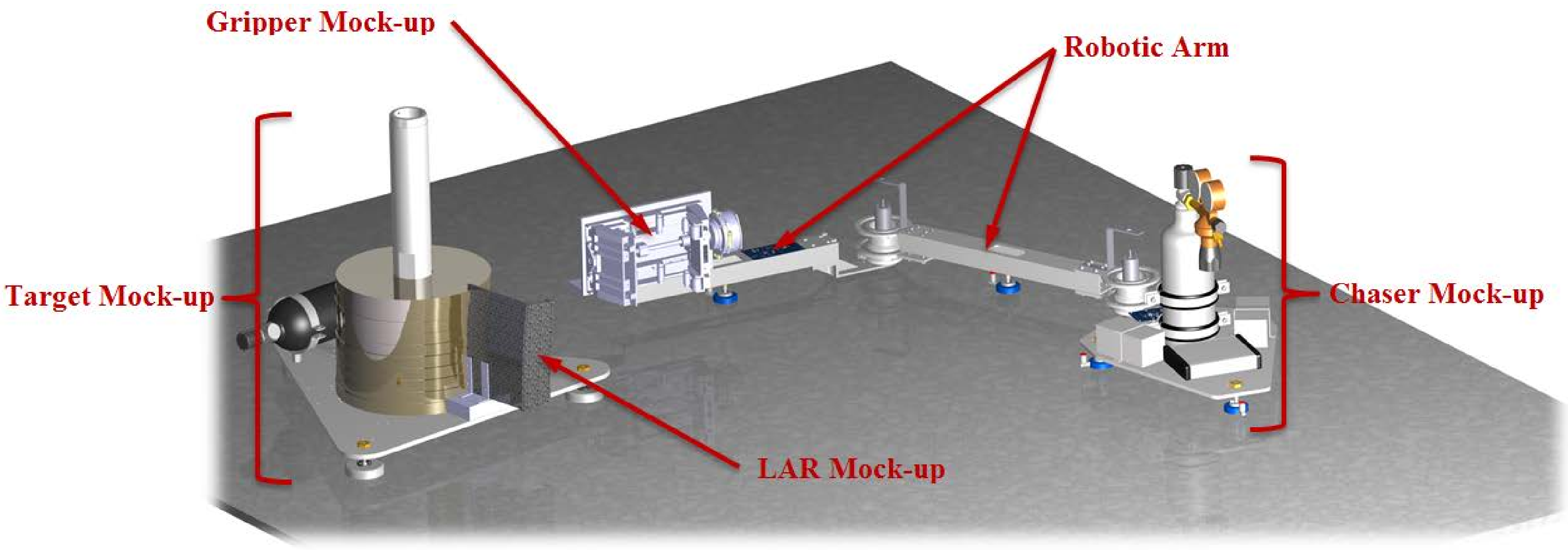
Mock-up of the chaser satellite with 2 DOF manipulator.

Experiments in the frame of e.deorbit project 3/5

Proposed scaling of system for tests on the air-bearing microgravity simulator in the frame of e.deorbit Mission Phase B1 study (scaling factor k = 0.3).

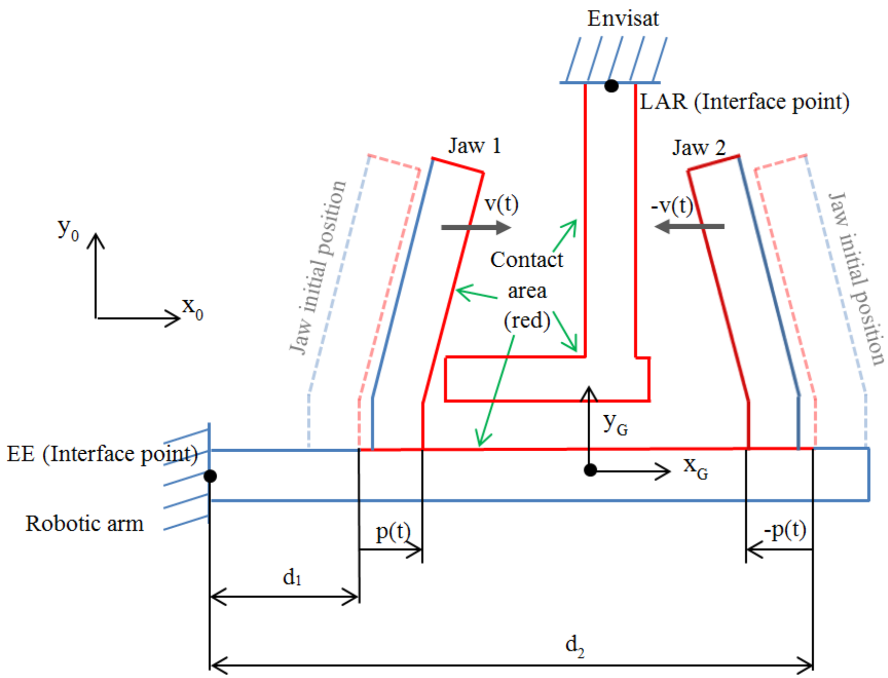
	Parameter	Scaling exponent *b*	Value before scaling	Value after scaling
1	Target mass [kg]	3	7900	213.3
2	Chaser mass [kg]	3	1500	40.5
3	Robotic arm length [m]	1	4.2	1.26
4	Gripper stroke [cm]	1	7	2.1
5	Time of grasping [s]	1	5	1.5
6	Chaser inertia [kg*m2]	5	762	1.85

Experiments in the frame of e.deorbit project 4/5

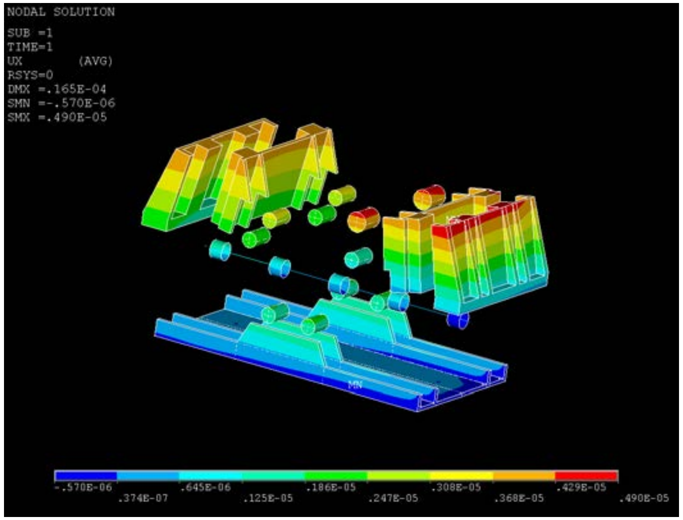


Experimental test set-up on the planar air-bearing microgravity simulator with chaser and target mock-ups.

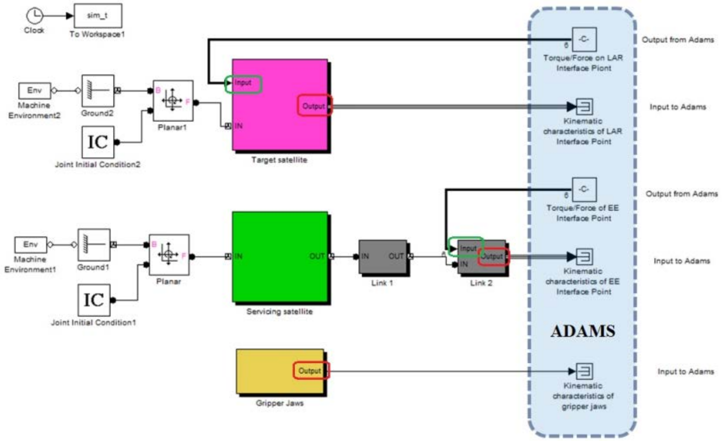
Experiments in the frame of e.deorbit project 5/5



Scheme of the gripper for contact analysis.



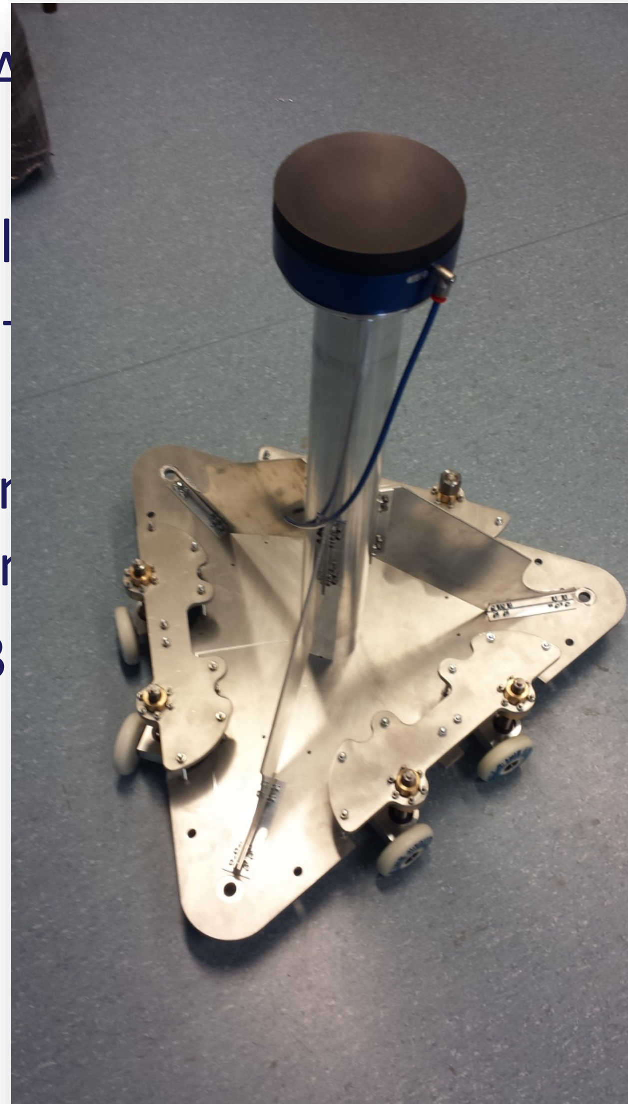
FEM Ansys simulations.

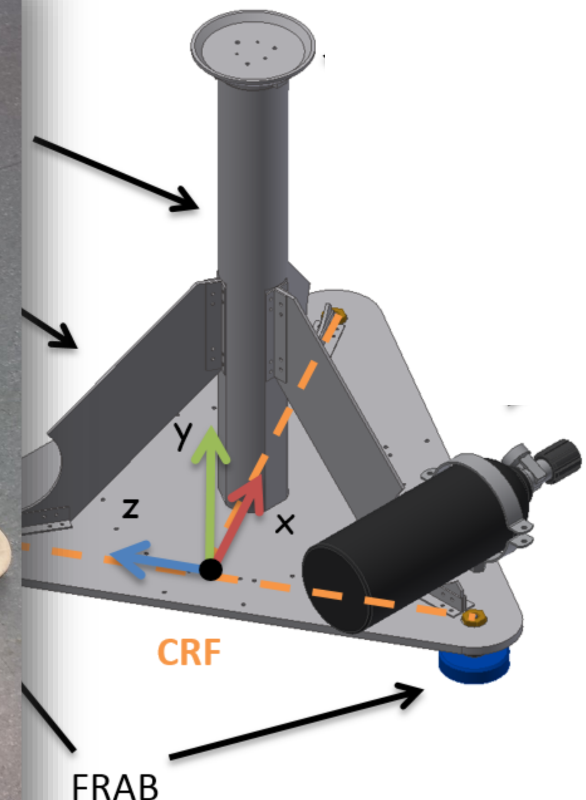


Matlab „Simulation tool for space robotics" with added contact module.

New platform for target mock-up

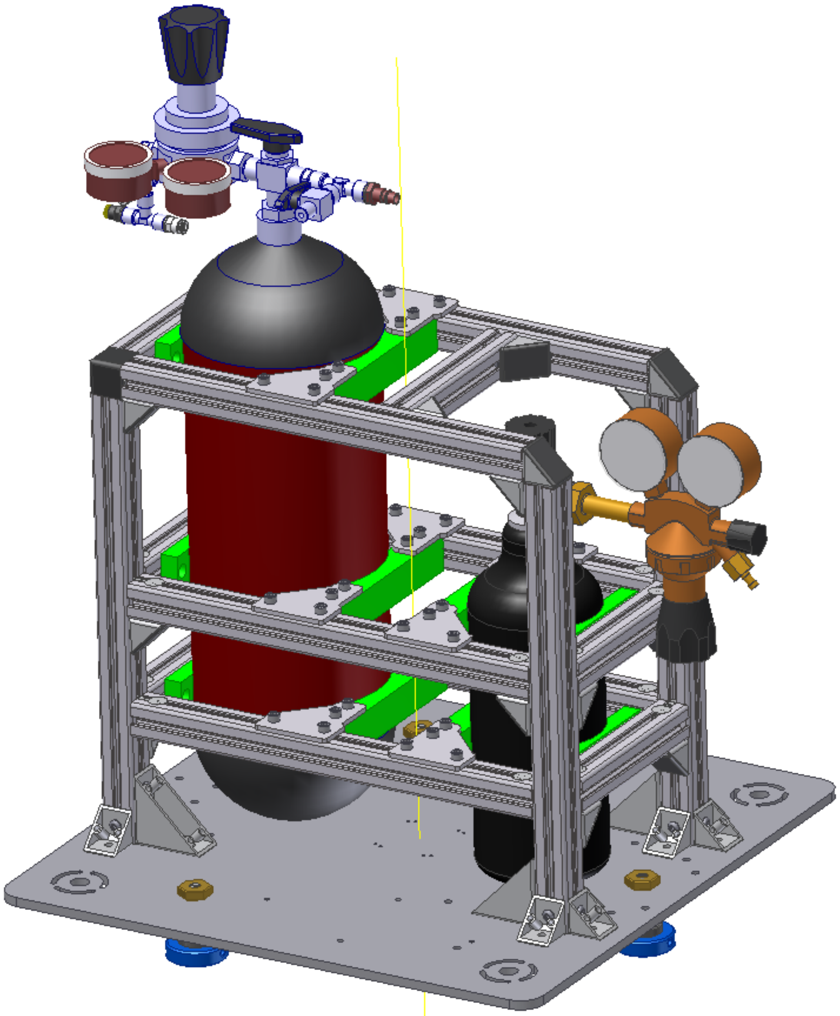
- On this platform LA
will be mounted.
- New air-bearing all
load capacity (mock-
above 200 kg!).
- Platform finished in
first tests are now un
- Possibility to add 3
rotational DOF with
bearing.



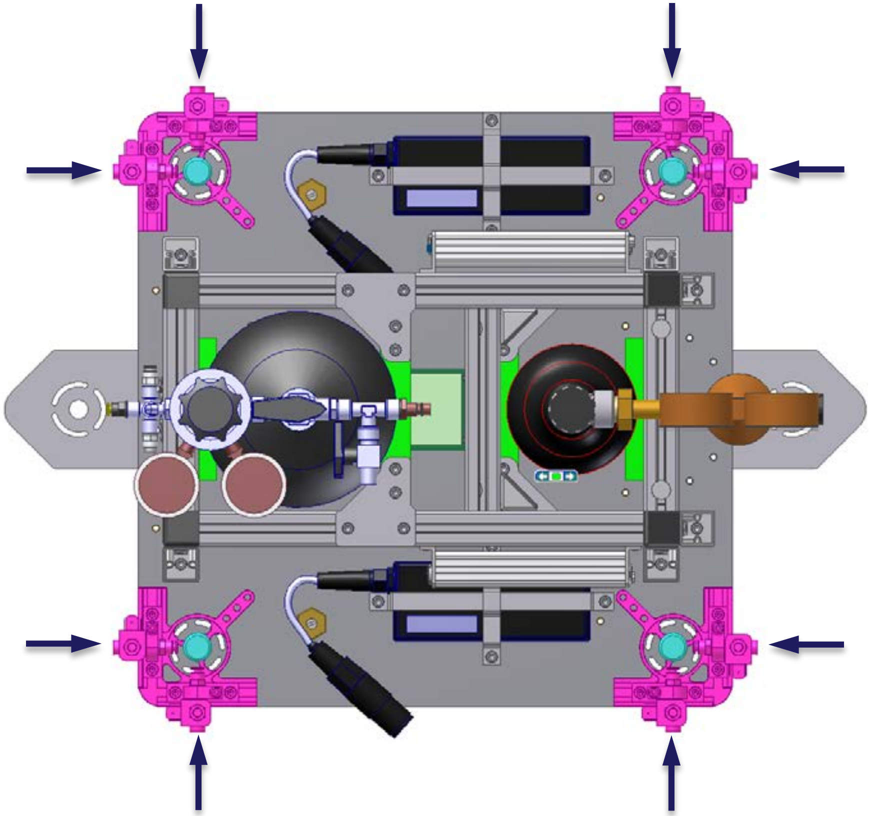


*rawing of a new air-bearing
platform (ready for tests).*

New platform for chaser mock-up

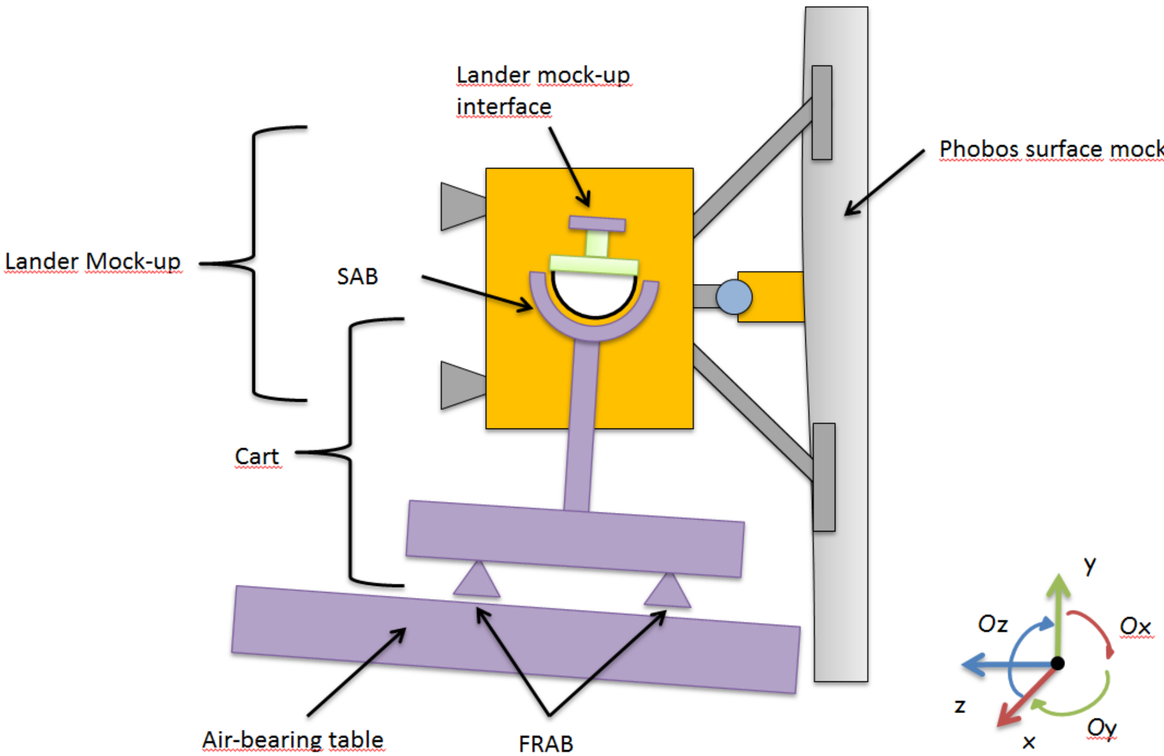


CAD drawing of a new air-bearing chaser platform (currently being integrated).



Top view of a new platform (arrows indicate positions of 8 thrusters).

Other applications of air-bearing test-bed



Experiments connected with Mars Moon Sample Return Mission (SAMPLER, REST).

Summary

- Planar air-bearing microgravity simulator is one of possible solutions to simulate microgravity conditions on Earth.
- Test-bed at CBK PAN was successfully used for numerous experiments related to space robotics.
- Experiments performed up to now involved planar satellite mock-up with 2 DOF manipulator.
- Planar air-bearing microgravity simulator can be used for various experiments related to ADR missions.
- Test campaign is currently planned in the frame of e.deorbit Mission Phase B1 study (contact forces and torques between the gripper and the LAR will be investigated).
- Recent upgrades to the test-facility: new air-bearing platforms (one with thrusters) and new pose estimation system.

Thank you
for your attention!