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Laboratory Study of Control Algorithms for Debris Removal Using CubeSat

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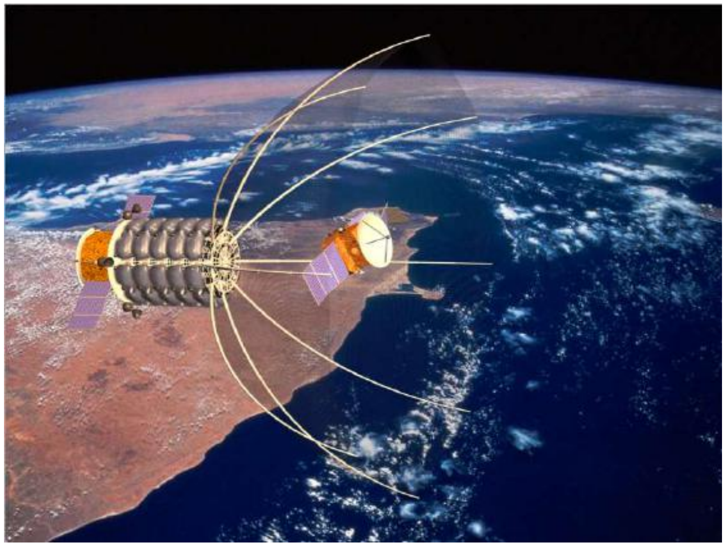
- ASDR Approaches
- Laboratory Facility Description
- ASDR imitation experiments
- Artificial potential-based control
- Conclusion

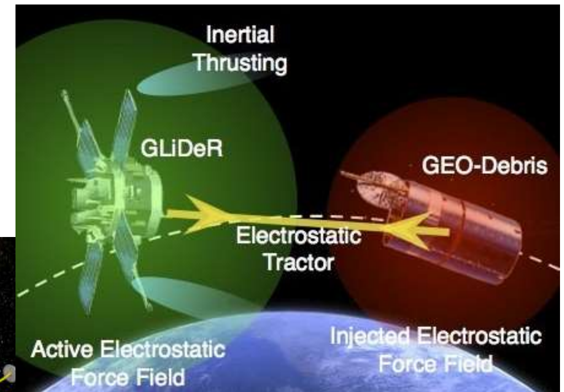
Active Space Debris Removal

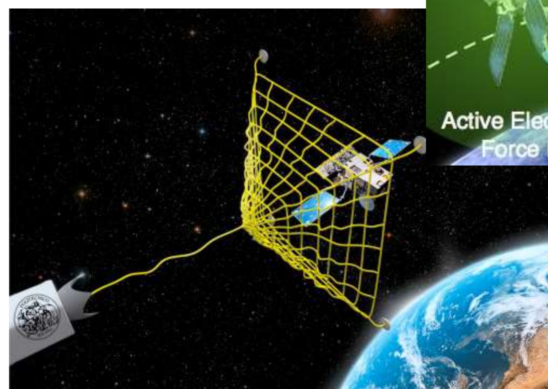
- Active spacecraft with capture system
- Non-cooperative space debris
- The goal is to capture the debris and change its orbit

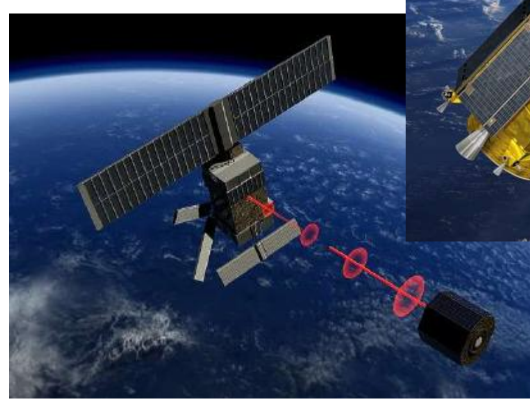


Capturing Systems

- Electrostatic tug
- Net on a tether
- Harpoon on a tether
- Space robotic manipulator
- Magnetic capture

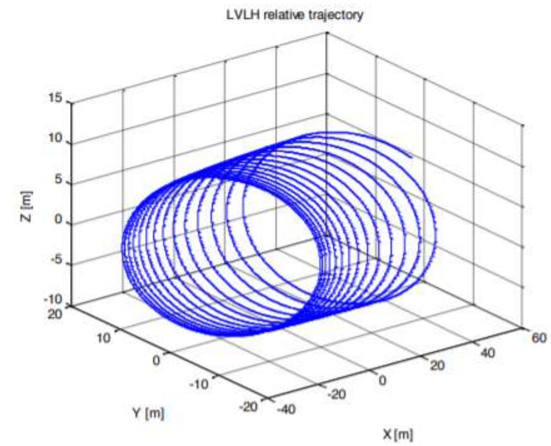




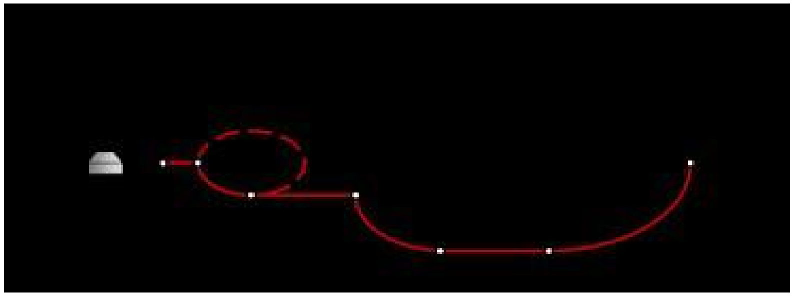


Main Stages of ASDR

- Rendezvous with debris
- Inspection of the debris motion for its parameters investigation
- Approaching and capturing
- Attitude stabilization after the capture
- Changing the orbit of the spacecraft-debris system



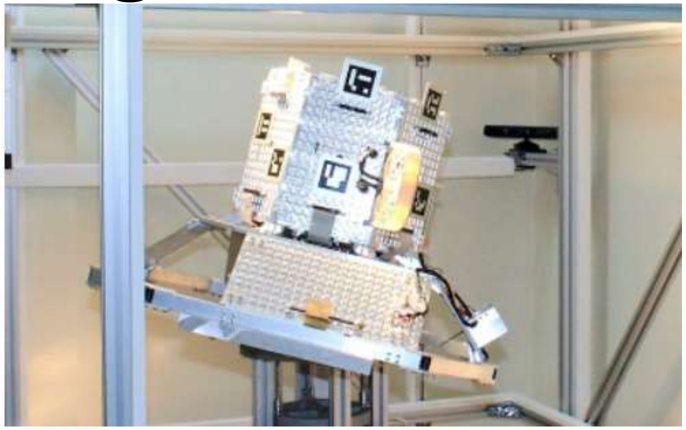
Relative trajectory for inspection



A sequence of relative trajectories during ASDR

Laboratory Testing of the Satellite Motion Control Algorithms

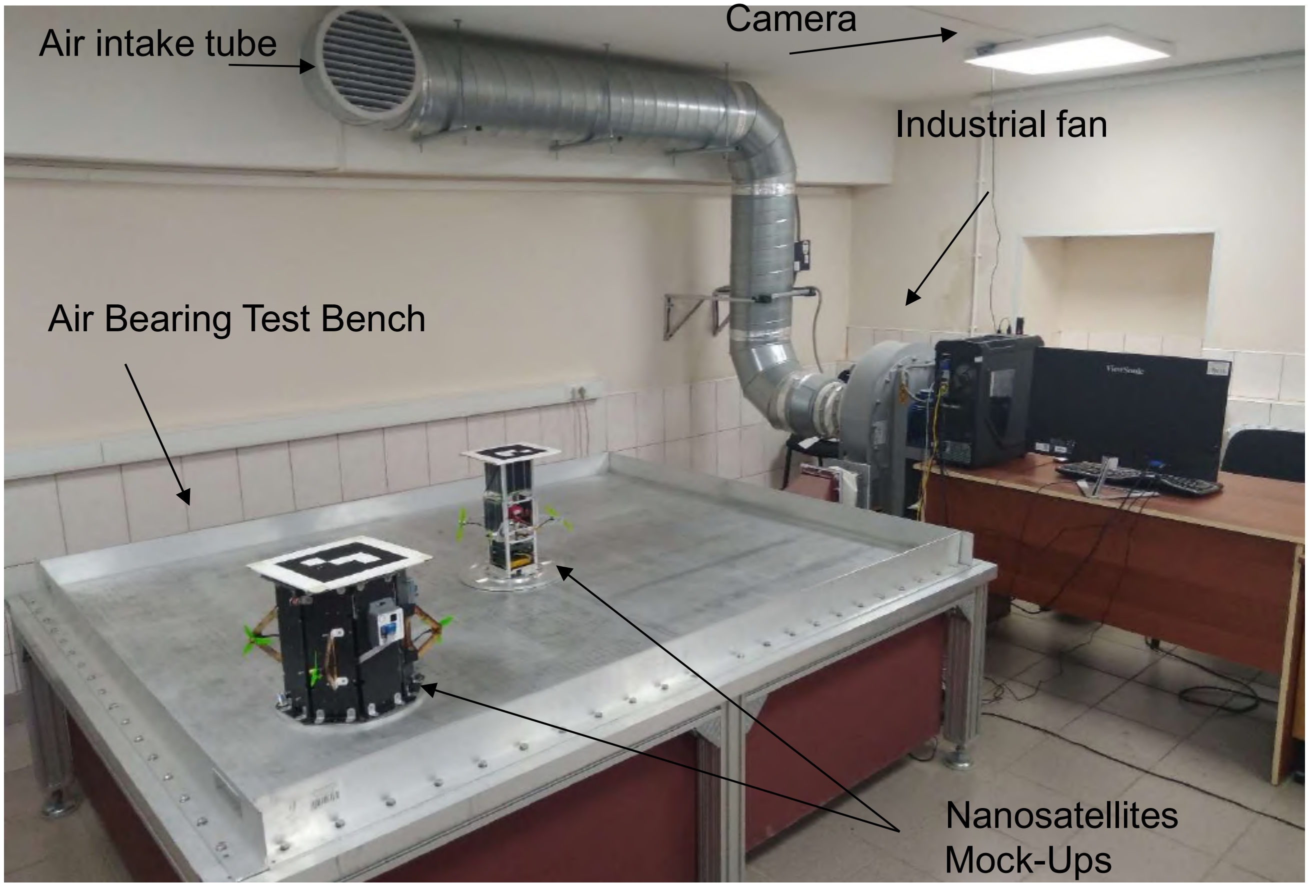
- Special laboratory facilities allow to test motion control algorithms
- Two types of facilities for
  - Three-axis attitude control system
  - Planar formation motion control system
- The planar air bearing laboratory facility is developed in the Keldysh Institute



Laboratory facility for the attitude motion control (developed by SputniX Ltd)

Planar air bearing table (developed in Surrey University)

Laboratory Facility for Formation Motion Simulation

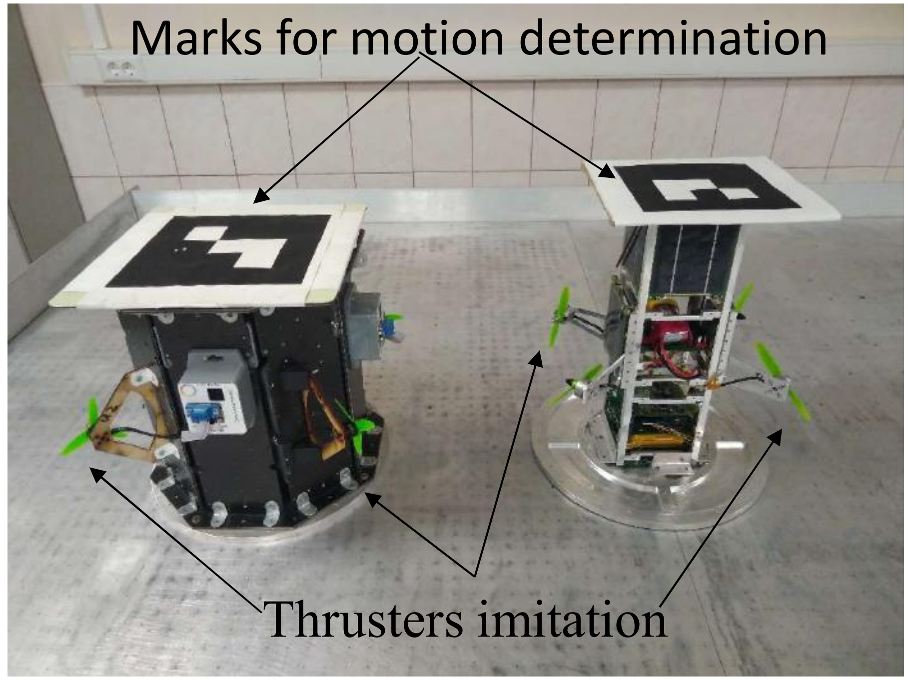


Laboratory Facility COSMOS
(Complex for Satellites MOtion Simulation)

Nanosatellites Mock-Ups

Mock-ups include:

- Onboard computer Raspberry PI
- Power supply system
- Communication system
- Sensors for motion determination
- Actuators:
  - one-axis reaction wheel
  - 4 ventilators imitating thrusters
- Wi-Fi channel



Mock-up based on TabletSat Constructor

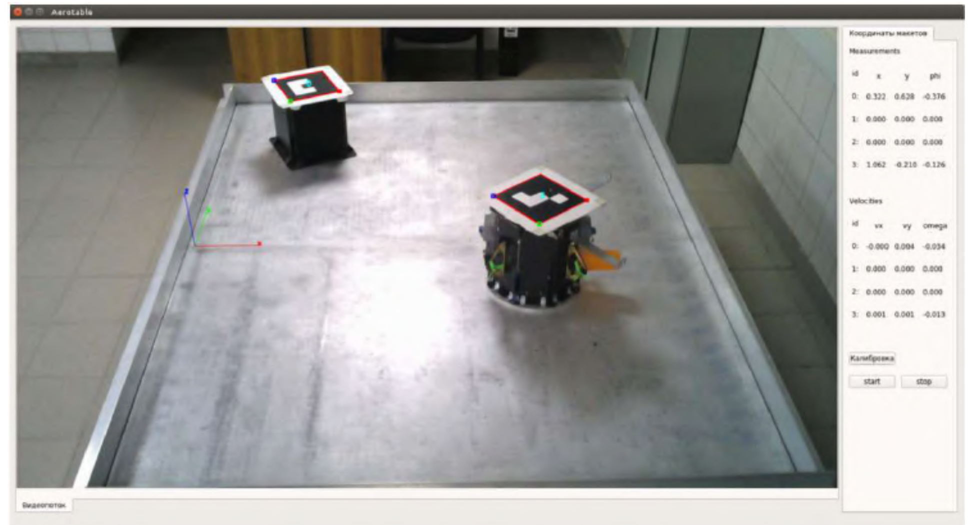
Mock-up based on 3U CubeSat

Mock-ups motion model:

$$\ddot{\mathbf{q}} = \mathbf{u} + \mathbf{d},$$

$$\mathbf{q} = \begin{bmatrix} x \\ y \\ \varphi \end{bmatrix} \text{– position vector, } \mathbf{u} = \begin{bmatrix} u_x \\ u_y \\ u_\varphi \end{bmatrix} \text{– control vector, } \mathbf{d} = \begin{bmatrix} d_x \\ d_y \\ d_\varphi \end{bmatrix} \text{– disturbances}$$

Mock-Ups Position Determination



From perspective geometry:

$$x = f\frac{X}{Z} \qquad y = f\frac{Y}{Z}$$

In the pixel reference frame:

$$x = f_x\frac{X}{Z} + c_x \qquad y = f_y\frac{Y}{Z} + c_y$$

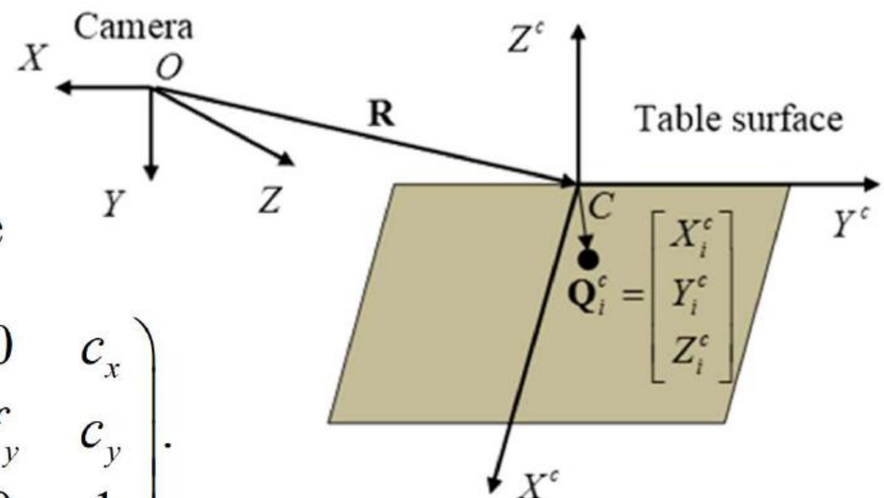
Correction for the pixel size:

$$f_x = s_x f \qquad f_y = s_y f$$

Ref. point position in matrix form:

$$\mathbf{q}_{corr} = \frac{1}{Z}MA(\mathbf{Q}_{стол} + \mathbf{R}), \quad \text{where}$$

$$\mathbf{Q} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \qquad \mathbf{q} = \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}, \qquad M = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix}.$$



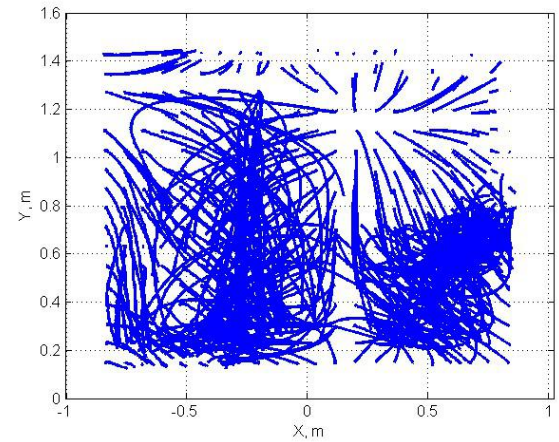
Disturbances on the Test-Bench

Sources of the disturbances on the table surface:

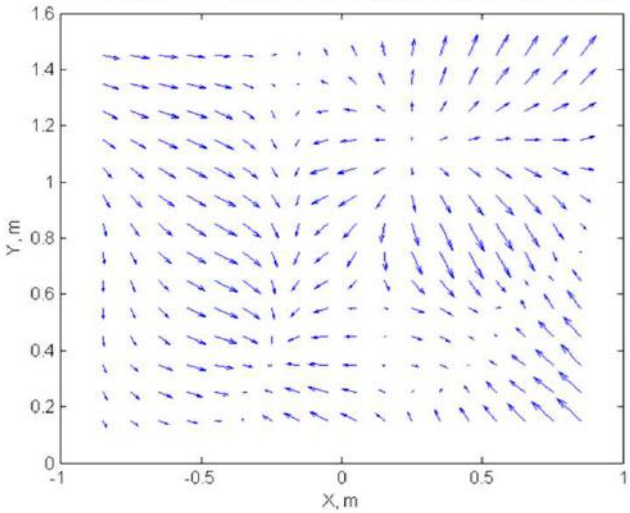
- Gravitational
  - Surface roughness
- Aerodynamic
  - The airflow is not uniform along the surface
  - The air cushion depends on mock-up mass and position of the center of mass

The disturbances are estimated experimentally and included in the control calculation

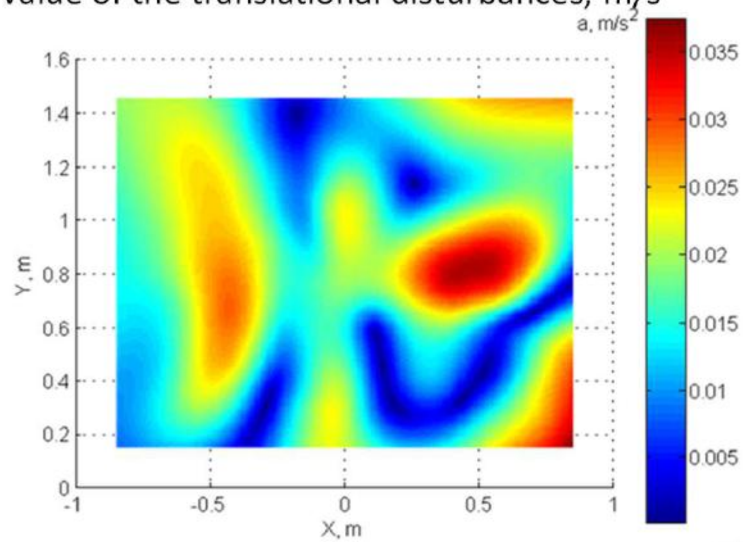
Free motion trajectories of the mock-up on the table surface



Direction of the translational disturbances



Value of the translational disturbances, m/s^2



Mock-Ups Control Algorithms

- Mock-Ups track the 6 DoF reference trajectories
- Lyapunov-based control is implemented
  - Lyapunov function

$$V = \frac{1}{2}\left(\mathbf{e}_r^T K_1 \mathbf{e}_r + \mathbf{e}_v^T \mathbf{e}_v\right),$$

where $\mathbf{e}_r = \mathbf{q} - \mathbf{q}_d$, $\mathbf{q} = [x, y, \varphi]^T$

  - Control algorithm

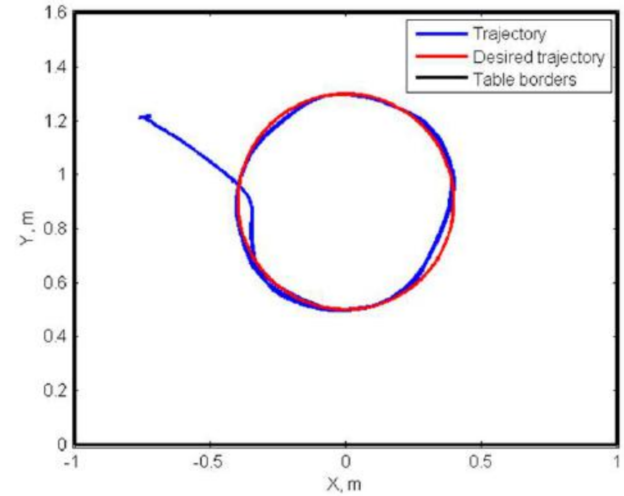
$$\mathbf{u} = -K_1 \mathbf{e}_r - K_2 \mathbf{e}_v + \ddot{\mathbf{q}}_d$$

- Control implementation by 4 ventilators

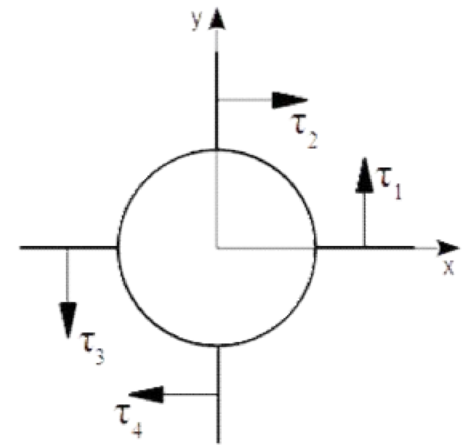
$$\tau_1 = 0.25\left(T_s / l + 2F_y\right) + \Delta,\ \tau_2 = -0.25\left(T_s / l - 2F_x\right) + \Delta,$$

$$\tau_3 = 0.25\left(T_s / l - 2F_y\right) + \Delta, \tau_4 = -0.25\left(T_s / l + F_x\right) + \Delta,$$

$$\Delta = \left|\min\left(\tau_1 \quad \tau_2 \quad \tau_3 \quad \tau_4\right)\right|$$



Example of the circular reference trajectory tracking



Scheme of ventilators placement and control forces

Features of the ASDR Imitation on the Laboratory Facility

Inspection

- Satellite moves along the circular relative trajectory
- Its camera directed to the debris for the observing

Phasing

- Satellite achieves required position on the circular trajectory for docking
- Its attitude track the attitude of the debris

Approaching

- Radial relative trajectory is decreasing until the magnetic capturing

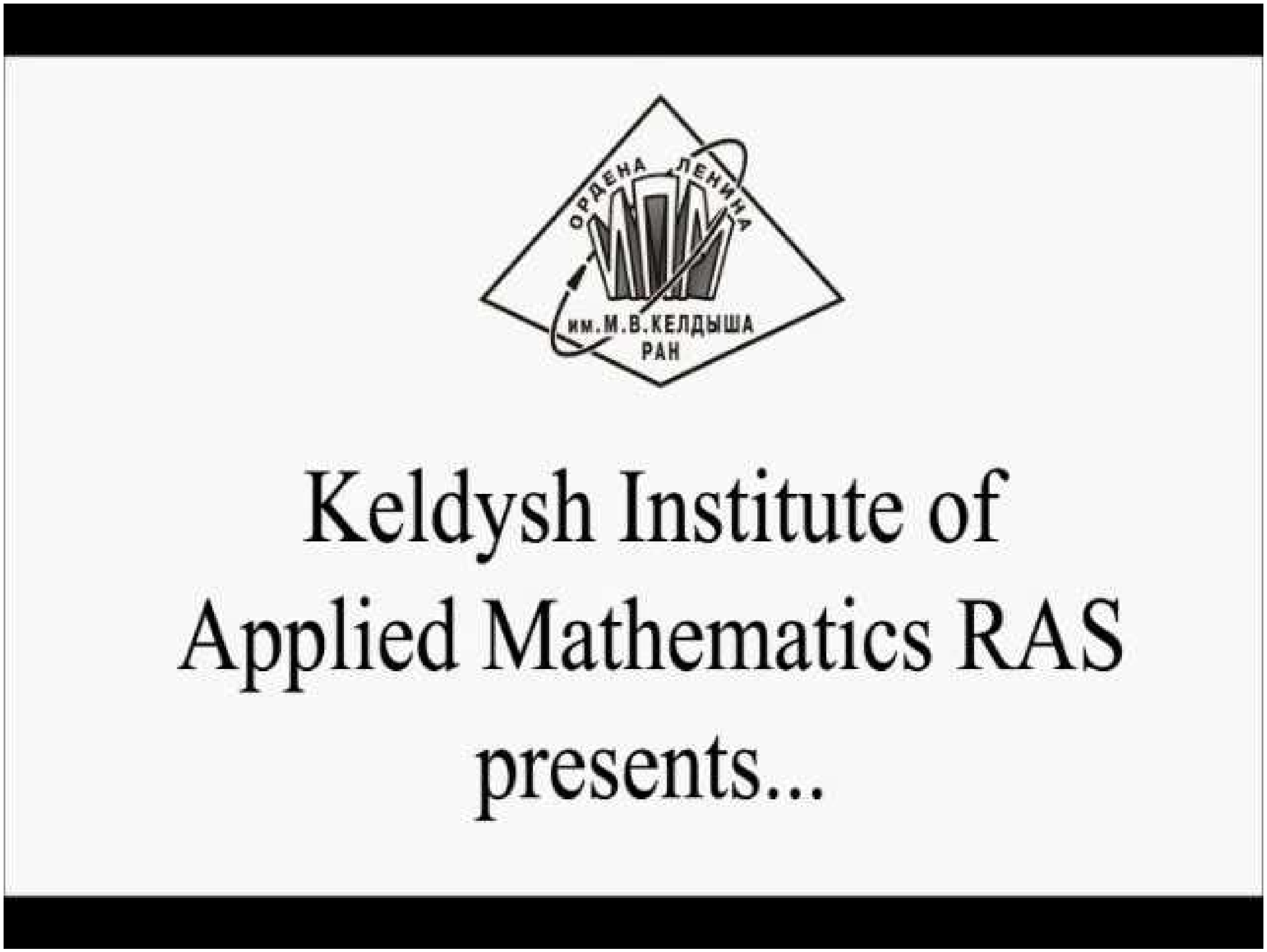
Stabilization

- Angular velocity damping and stabilization after the debris capturing

Deorbiting

- Changing the debris position on the table surface

ASDR Imitation Experiment

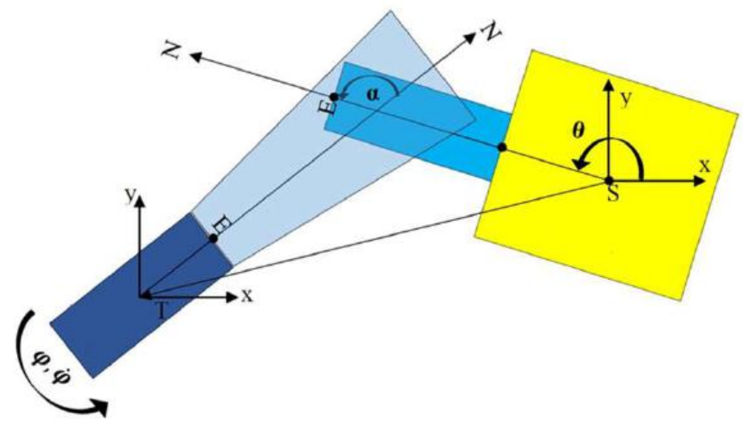


Docking using potential-based control

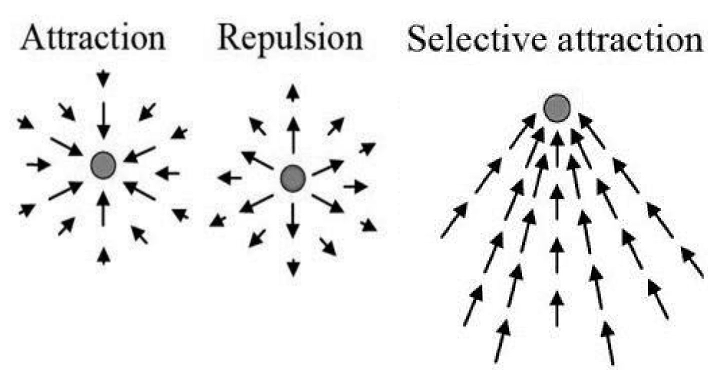
- The docking is possible only to one side of the debris object during the approaching phase
- The approaching and collision avoidance control can be calculated using the repulsive and attractive terms in the potential function:

$$V = -c_a e^{\frac{-z}{l_a}} + c_r e^{\frac{-z}{l_r}}, \quad \mathbf{F} = -\nabla V$$

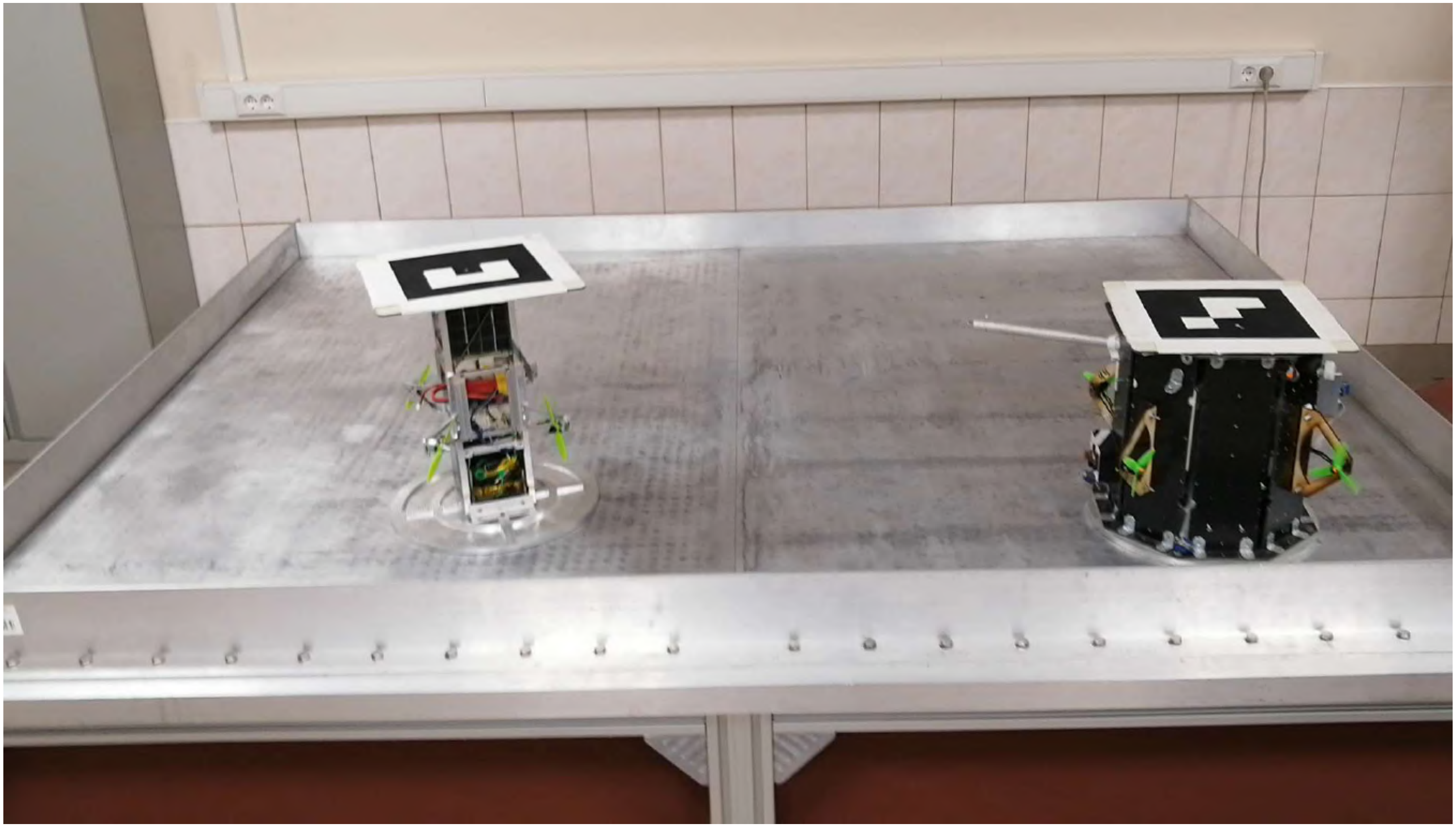
- The equilibrium distance is calculated using the stability analysis
- The repulsive force term is eliminated in the area acceptable for the docking



Relative position and attitude of the mockup and the target and the area acceptable for the docking

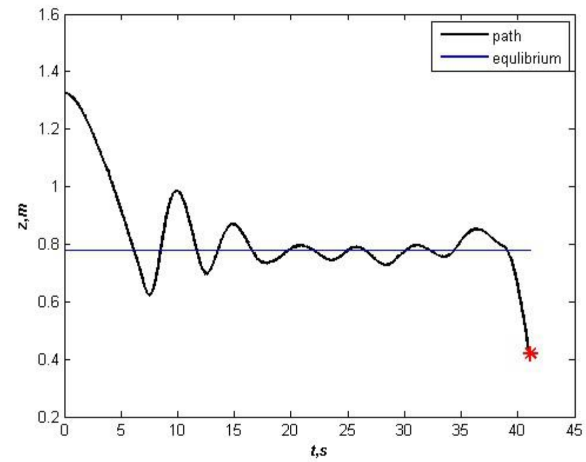


Potential-based Control Experiment

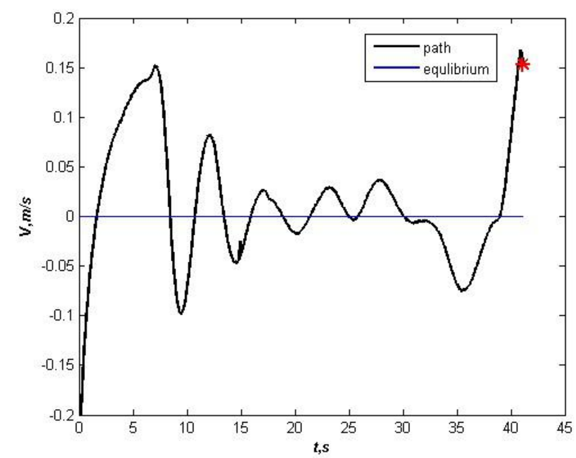


Experiments Results Discussion

- The advantages of the potential-based control approach
  - Simple feedback control
  - Collision avoidance term
  - Low computational cost
- Drawbacks:
  - The equilibrium distance should be carefully precalculated
  - The docking may be unsuccessful in case of high debris angular velocity



Relative distance during the experiment



Relative velocity during the experiment

Conclusion

- Active space debris removal imitation on the planar air bearing table should take into account laboratory facilities features
- The laboratory experiments help to understand the ASDR most critical factors for each control stage
- Potential-based control algorithm is successfully tested in the laboratory

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Thank you for your attention!