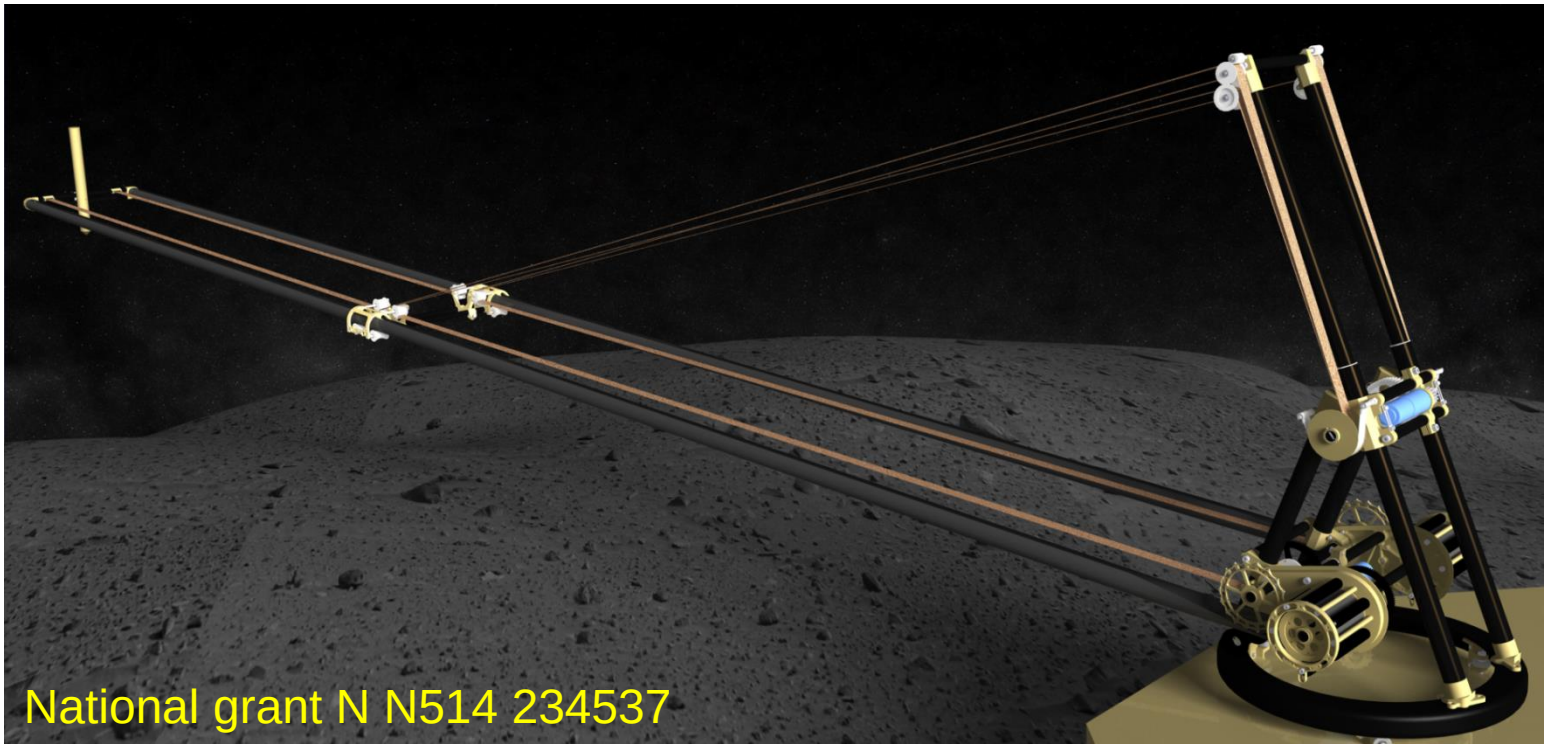
PROTOTYPE OF ULTRA-LIGHT PLANETARY MANIPULATOR – DESIGN, TESTS AND SIMULATIONS



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OUTLINE

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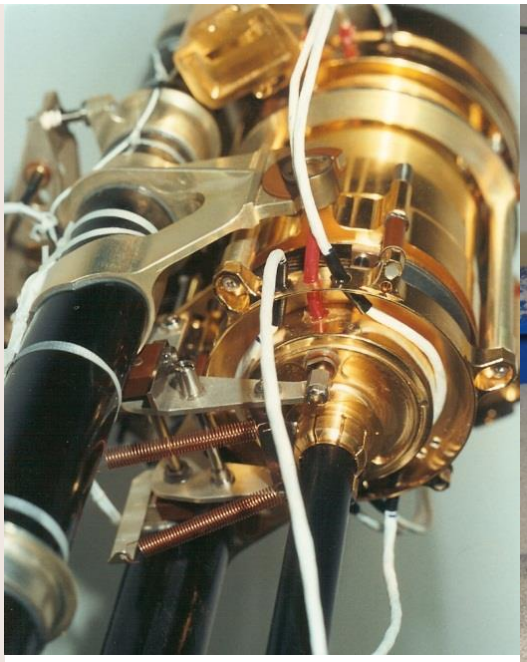
   - Simulations and test results - comparision
5. **ULPM performance and conclusions**

SRC space mechanisms heritage

MUPUS Penetrator
(on its way to comet 67P)

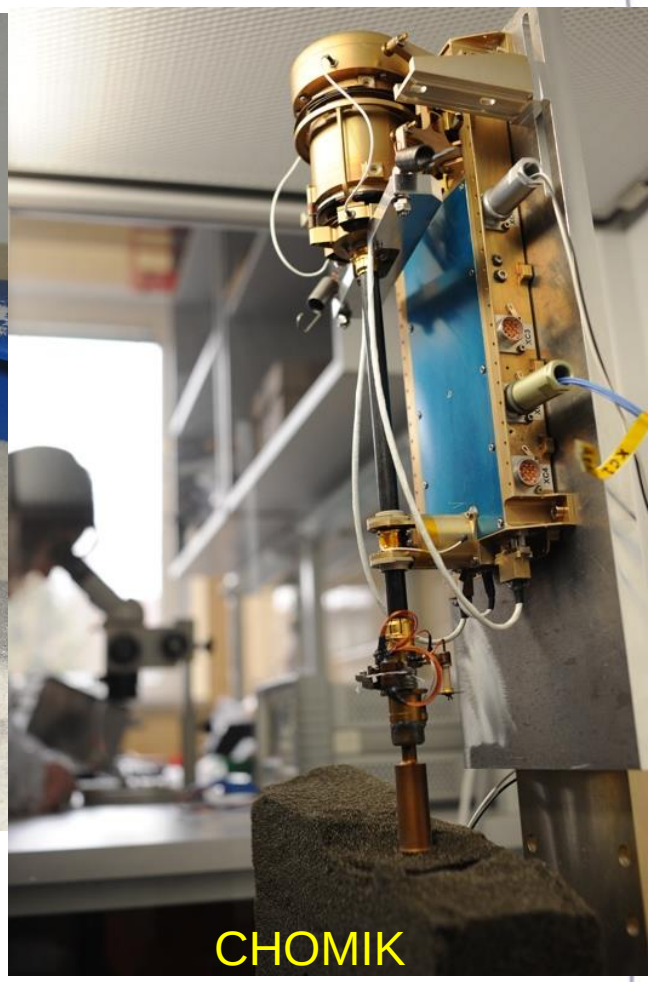


Electromagnetic Hammering Device (hight reliability and 4 levels of strokes energy)

Mole Penetrator

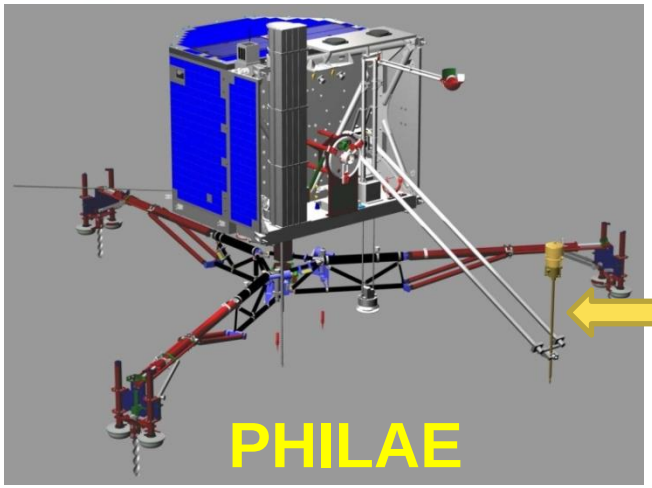
(2.2J, 0.5kg

Tested up to 5m in Lunar regolith analogue)



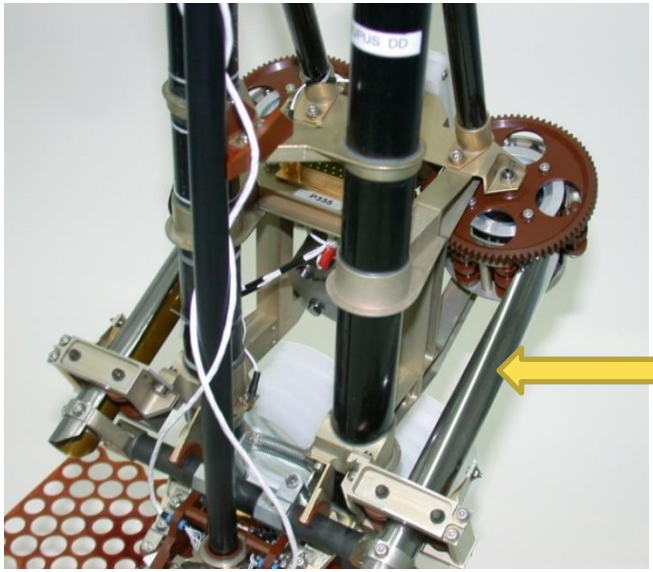
Sampling Penetrator

MUPUS manipulator

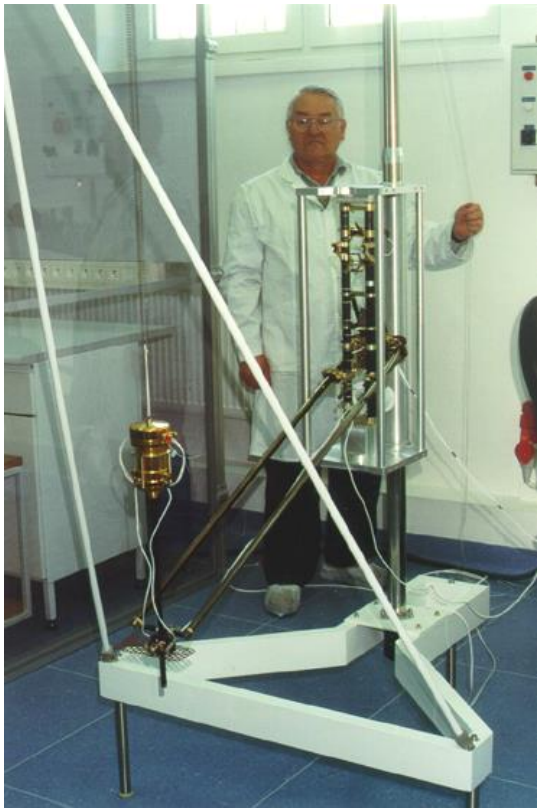


FUNCTIONS:
1. **Penetrator deployment**
2. **Insertion support**
3. **Depth progress measurement**
4. **Retraction after separation**

MUPUS Penetrator



Functional test at SRC



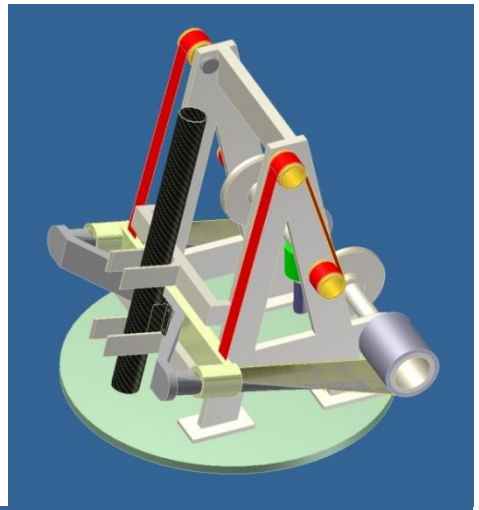
Tubular Boom

ULPM conceptual idea

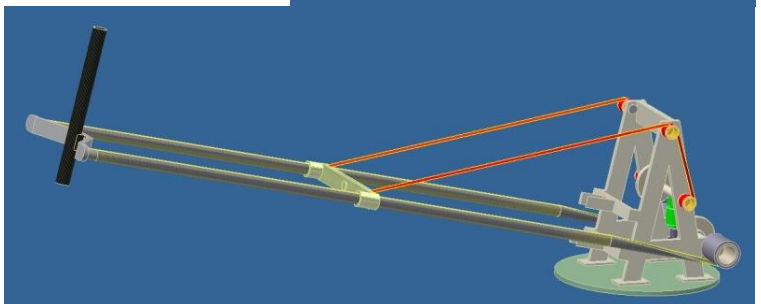
The idea for ULPM is an extension of the MUPUS device

Originally proposed for Exo-Mars HP^3 Instrument

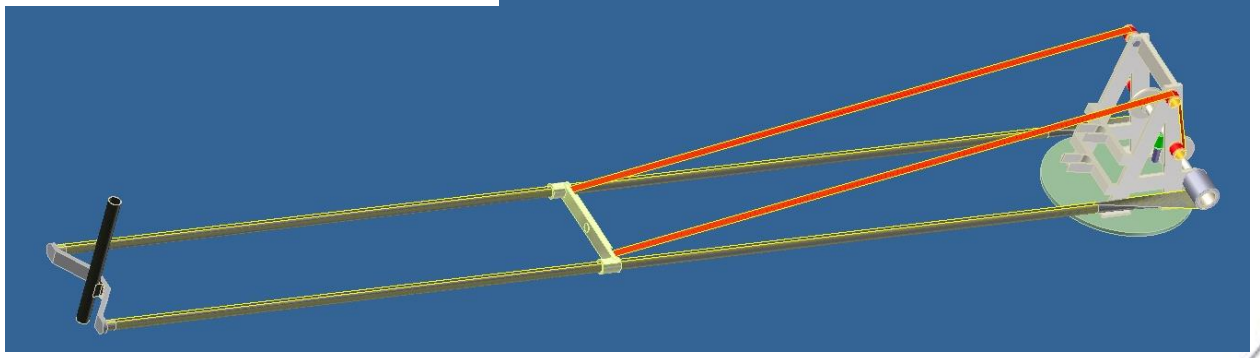
1. **3 DoF: extension, tilt, horizontal rotation**
2. **Main part: parallel tubular booms**
3. **Adventages: 3m range, 2-3kg**



Stowed

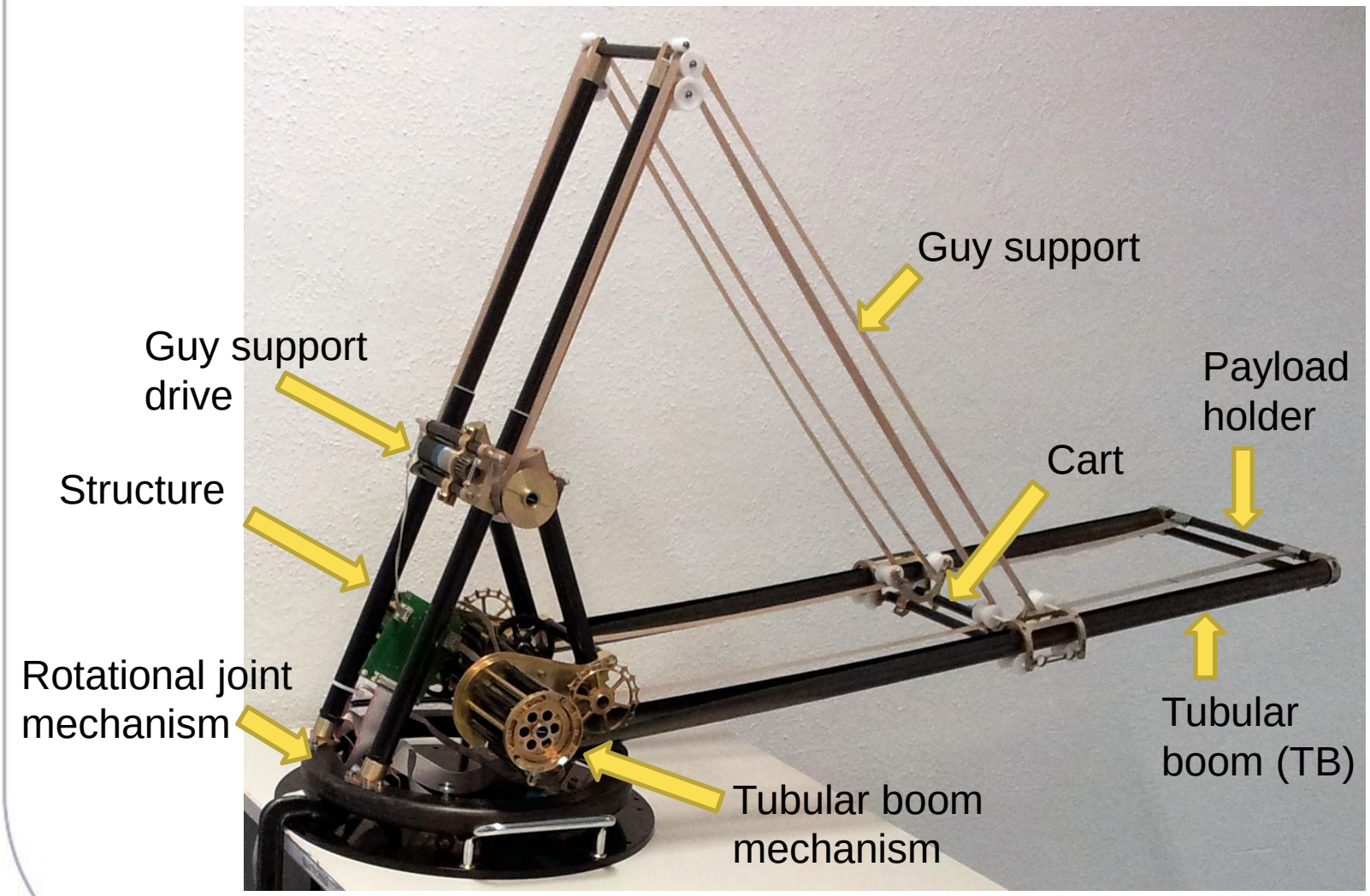


During tilted-up extension



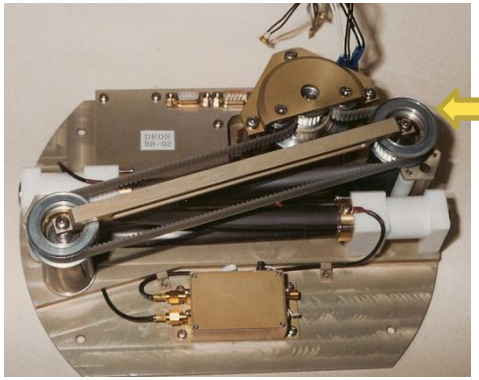
After full extension and lowering

General view of the ULPM prototype



Tubular booms

EXPERIENCE:



antenas' deployments – **TRL 9 (3x)**
MUPUS manipulator – TRL 8
(different prototypes
TRL 2-3)

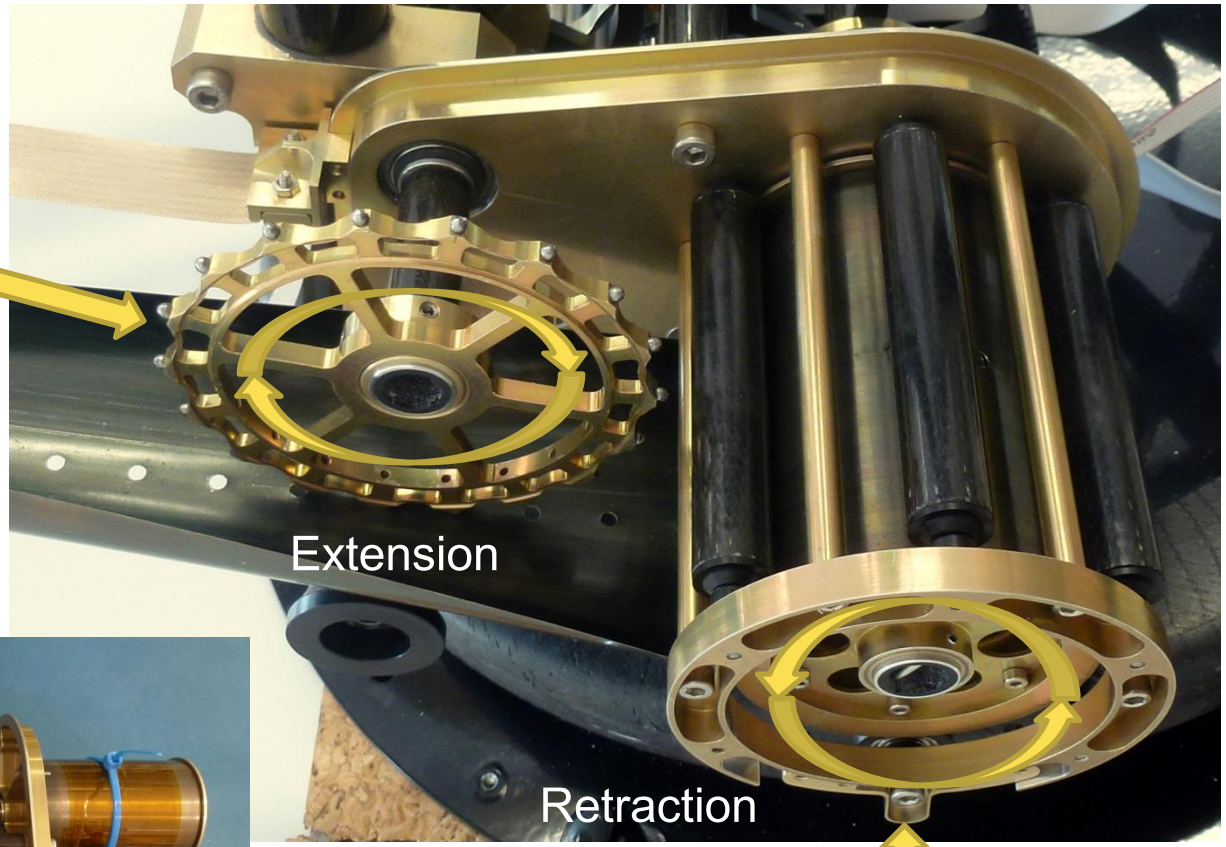
TB TYPES:
- ø6x0.05 mm, berilium bronze, 8 g/m, (under development in Poland)
- ø15x0.10 mm, stainless steel, 34 g/m, Ukrainian
- ø25x0.15 mm, stainelss steel, 90 g/m, Ukrainian (**used in ULPM**)

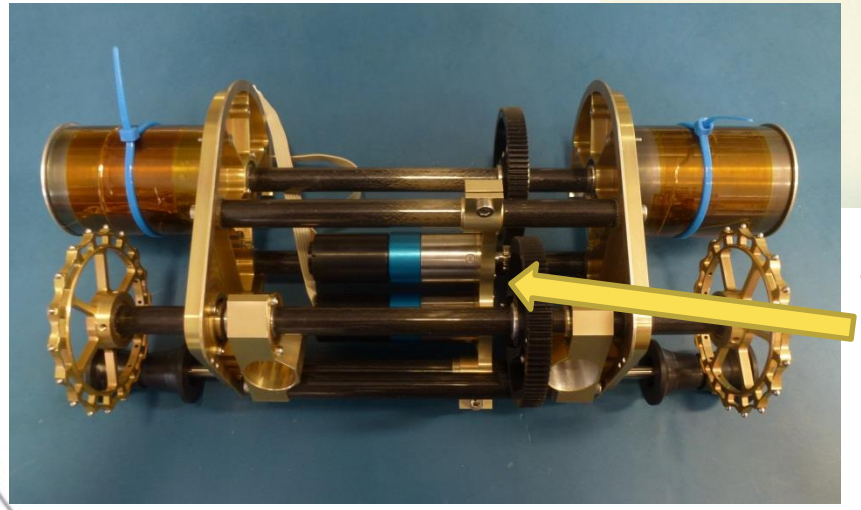
WEAK POINT: Low torsional stiffness of the open profile

Method – parallel booms (MUPUS, ULPM)

Tubular booms mechanism

Drive wheel with specially designed pins which cooperates with holes drilled in tb

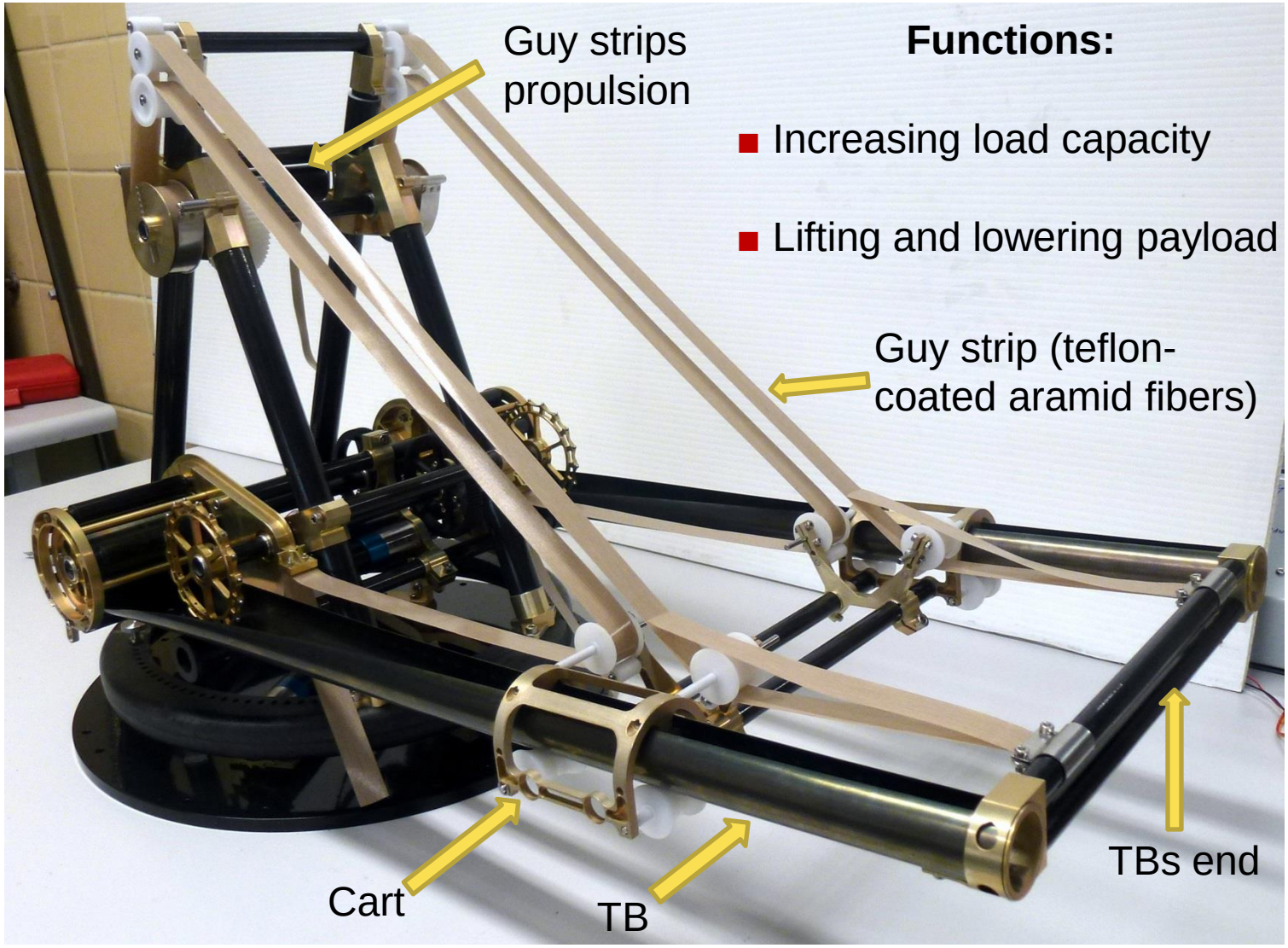




Tbs are propelled by two counter-rotating electrical DC gear-motors

Reel with rolled TB

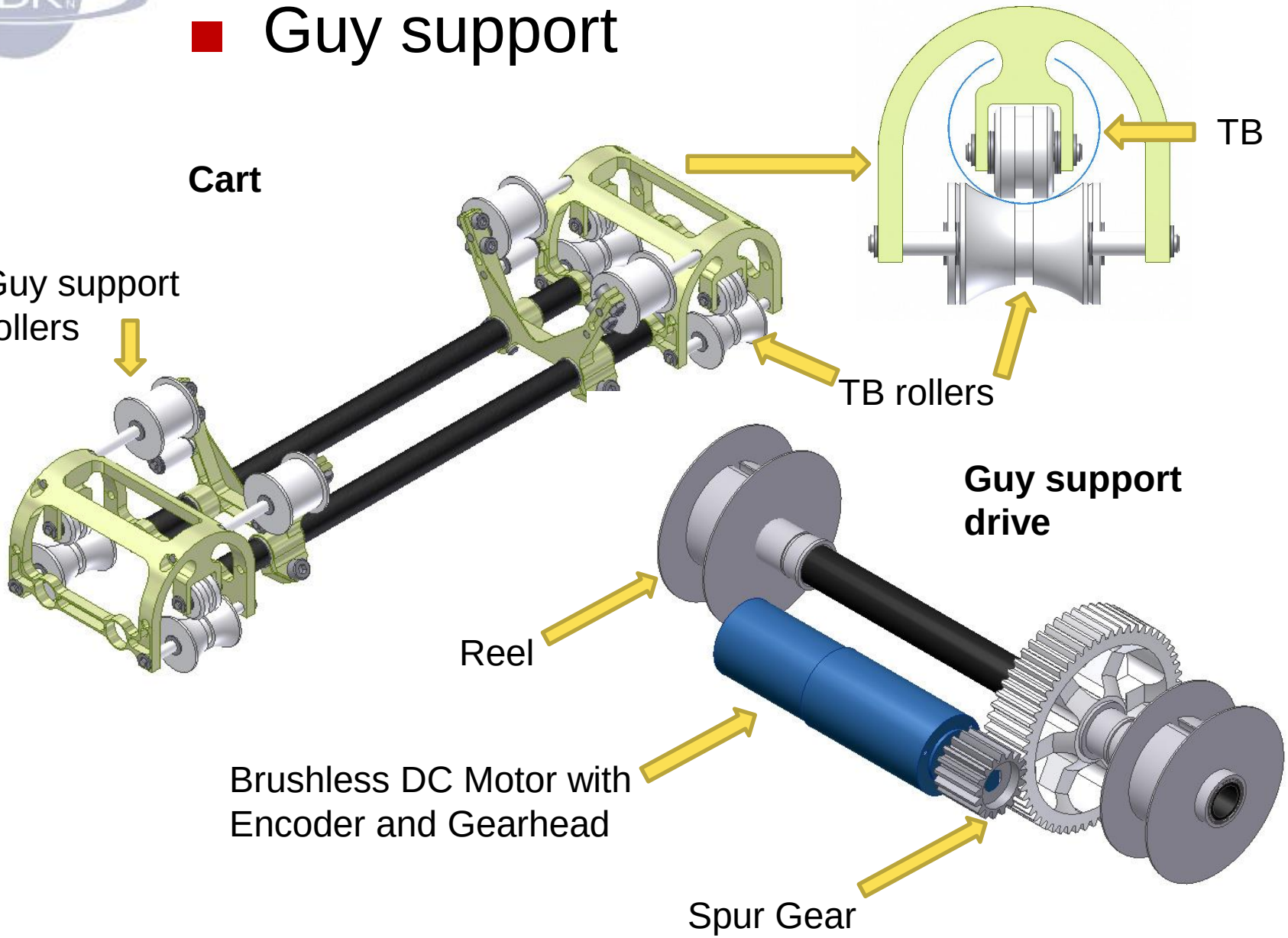
Guy support system



Functions:

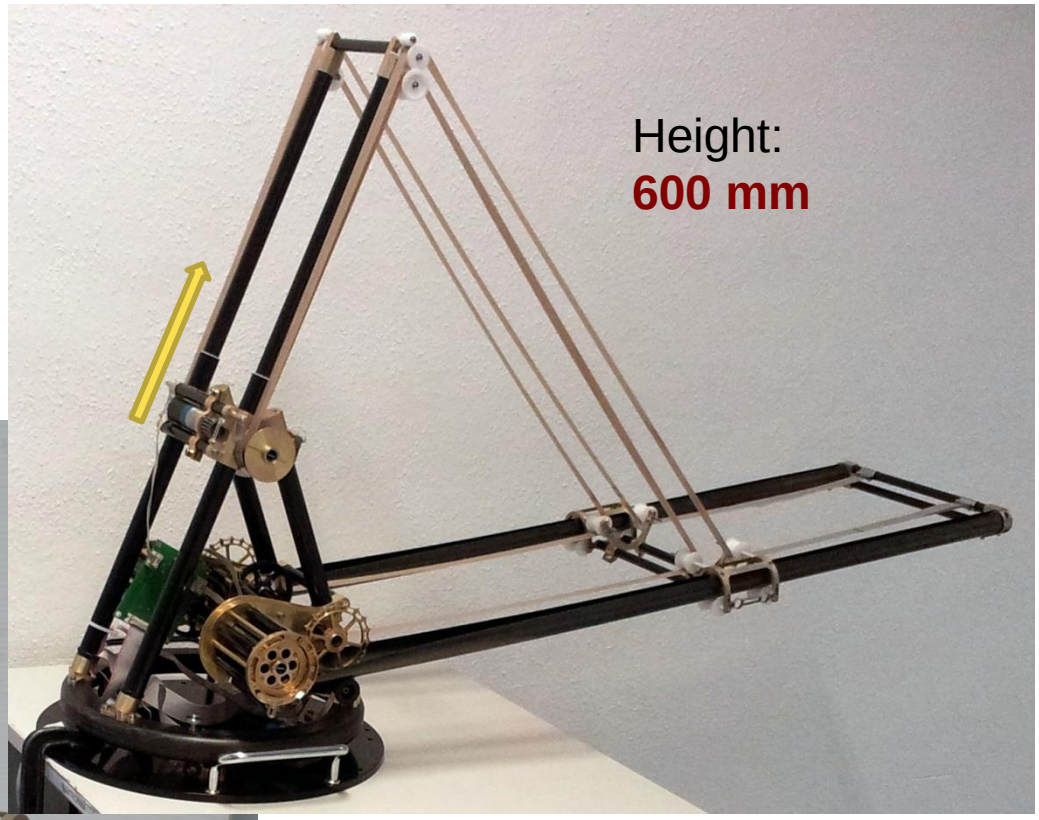
- Increasing load capacity
- Lifting and lowering payload

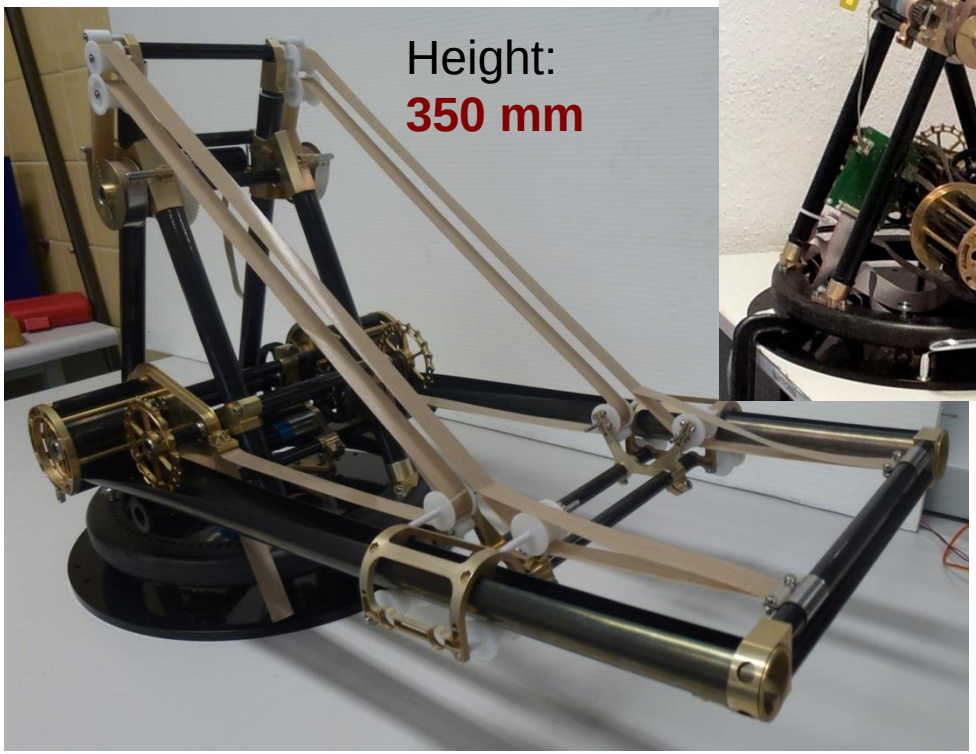
Guy support


TB
Cart
Guy support rollers
TB rollers
Guy support drive
Reel
Brushless DC Motor with Encoder and Gearhead
Spur Gear

Deployable structure

Deployable mechanism results in larger support angle between guy strips and tbs.



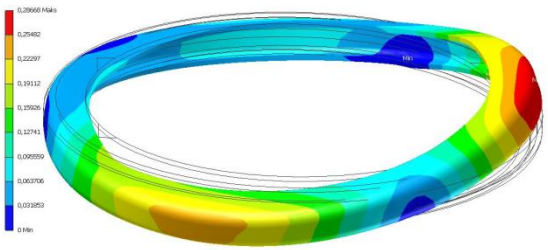


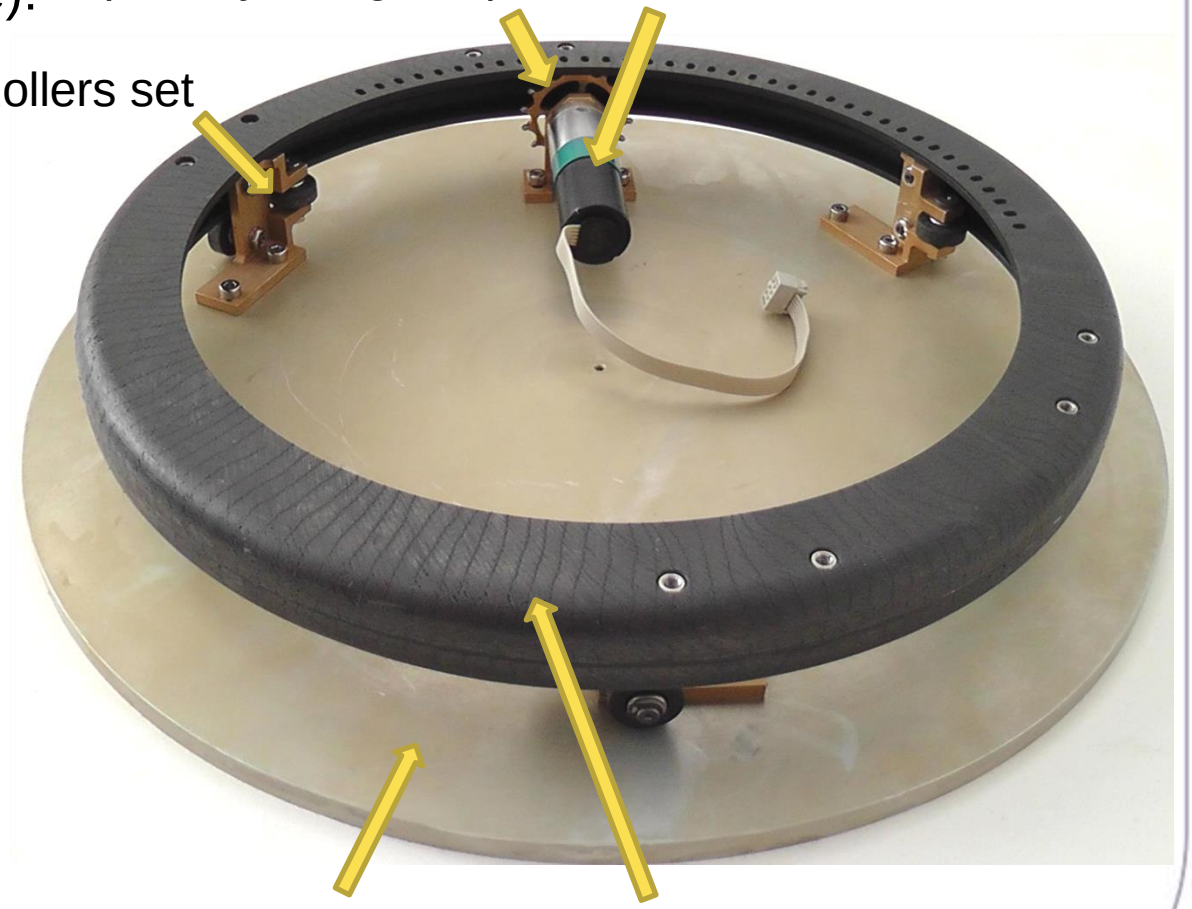
Almost the whole structure is composed of carbon fiber pipes:

- low weight
- high mechanical strength

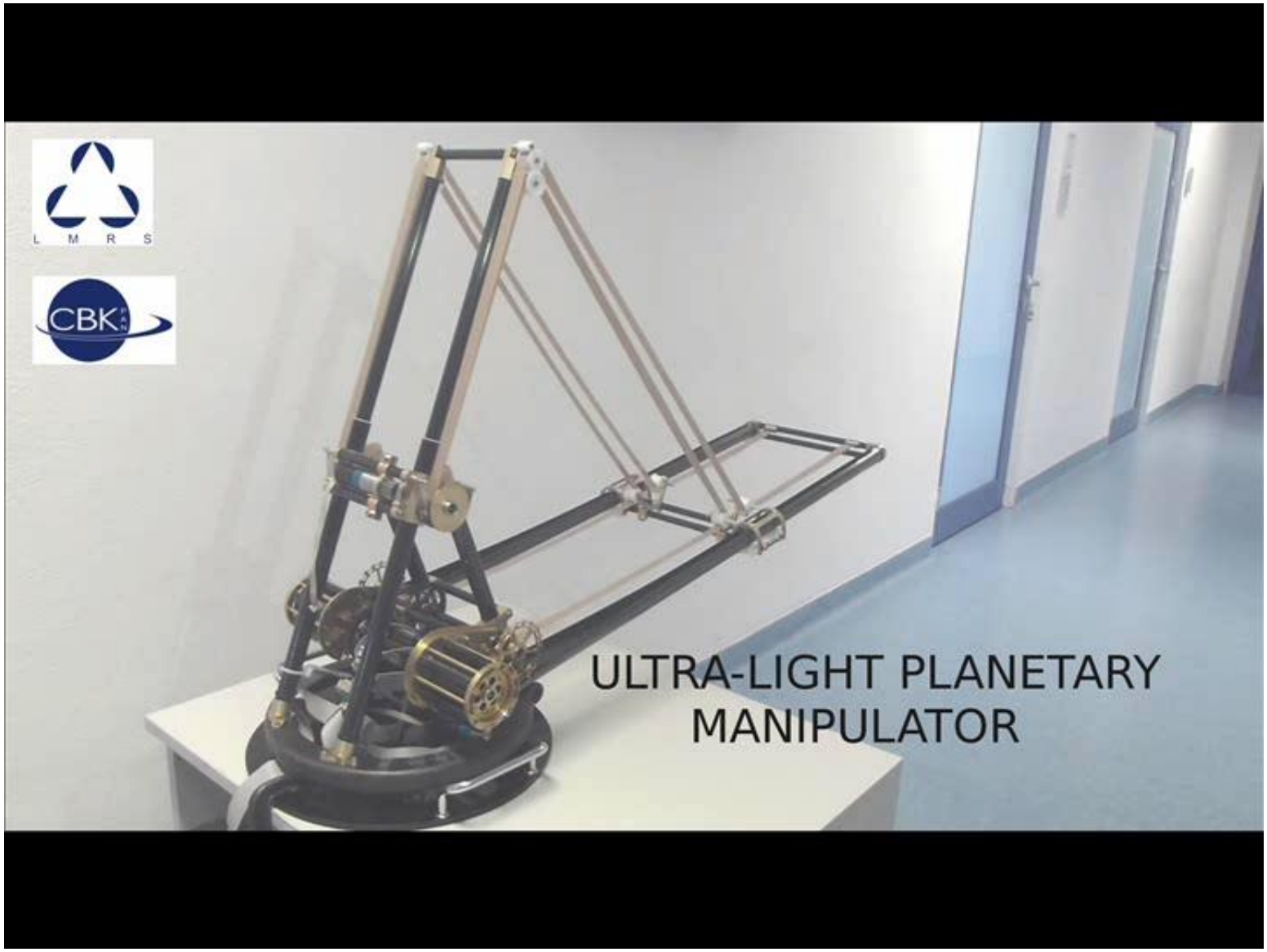
Rotational joint mechanism (optional)

- Mass (without base plate):
  0,6kg
- Size:
  Diameter: **300mm**
  Height: **45mm**
- Rotation speed:
  1 rev/min
- Rotation range:
  ± 60º
- Maximum load capacity:
  200N

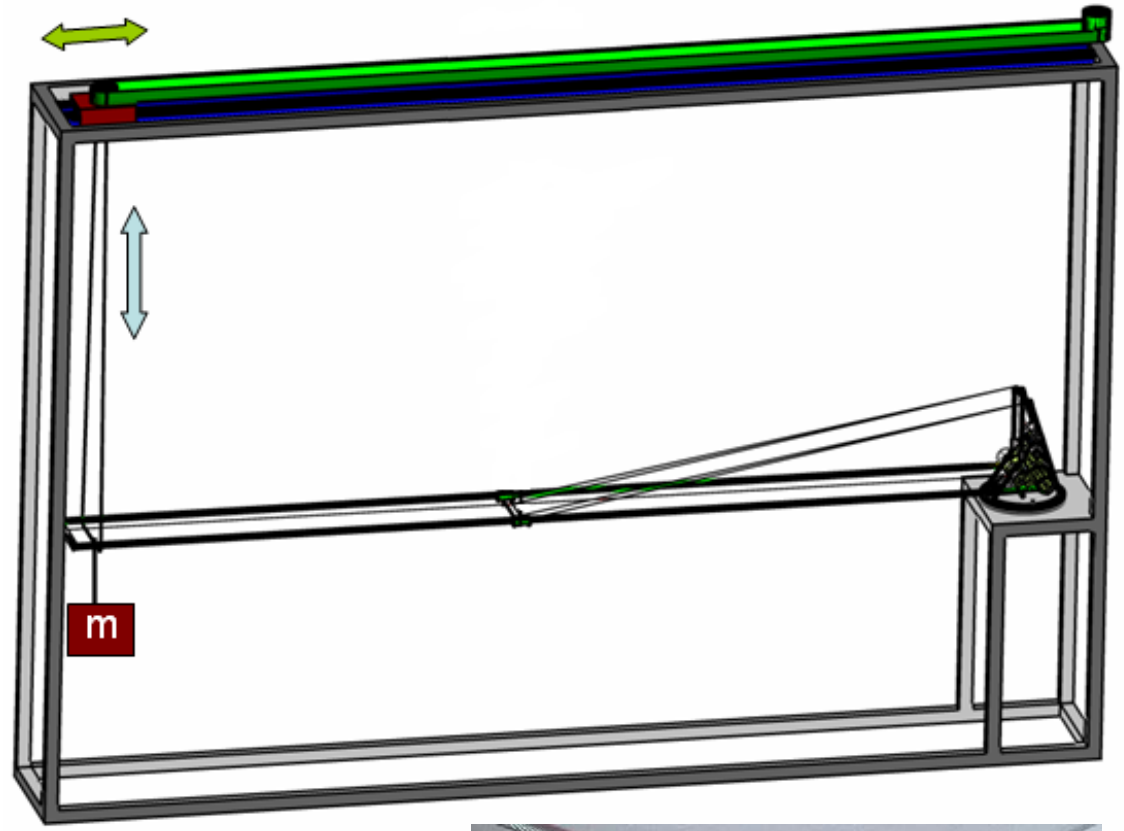




Functional test – 3DoF



Load test in simulated low gravity (1)



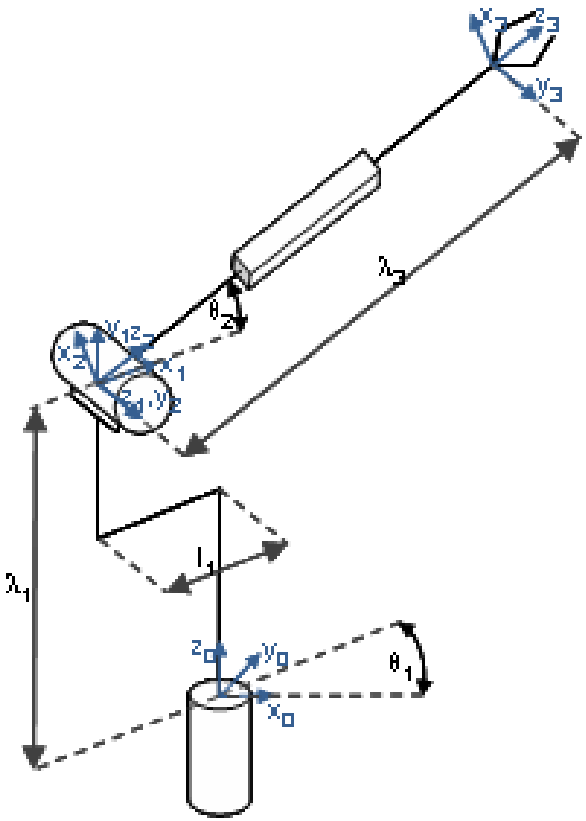
ULPM test bed with simulated low gravity conditions (moon gravity) - the load was compensated by spring hanged up on the specially designed cable cart. Dynamometer was showing the actual load value.

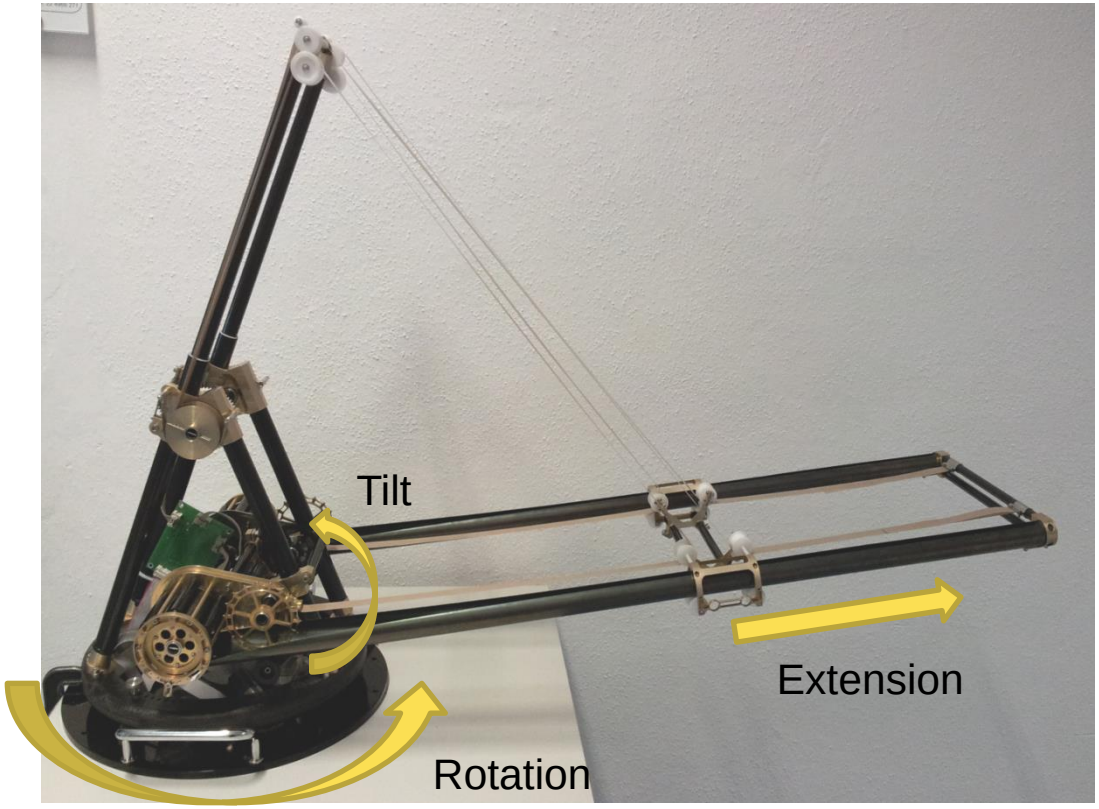
Load test in simulated low gravity (2)

(Movie)

Numerical simulations (1)

- Lagrangian approach was used to develop the numerical equation of motion.
- All kinematic pairs were assumed to be rigid.



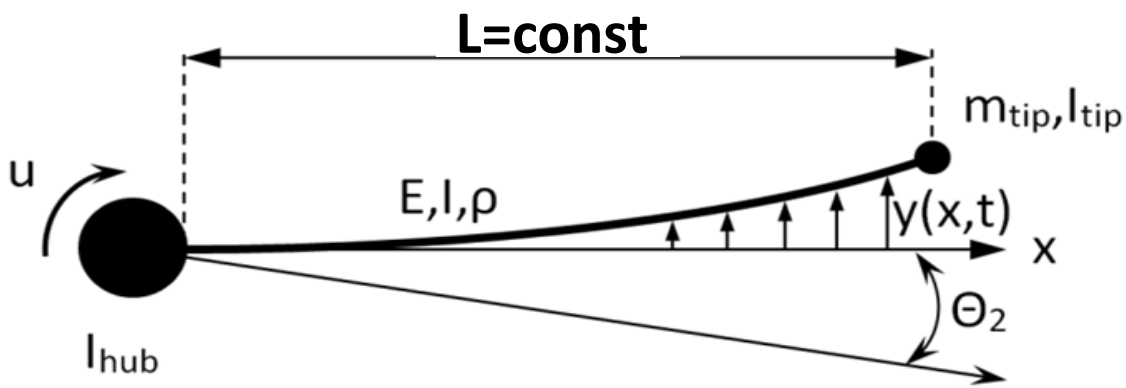


Manipulator's kinematic scheme with coordinate system

Numerical simulations (2)

Our assumptions:

- third kinematic pair is elastic,
- length of third element is constant,
- third kinematic pair consists of rigid second kinematic pair, elastic beam and tip at the end of beam,
- beam modelling is consistent with Euler–Bernoulli beam theory.



A simplified model of the manipulator arm:
I_{hub} – moment of inertia of rigid joint, I_{tip} – moment of inertia of tip, I – moment of inertia of arm cross-section, E – Young's modulus of tubular boom, ρ – tubular boom density

Numerical simulations (3)

System Lagrangian:

$$Lag = \frac{1}{2}\cdot I_{hub}\cdot \theta(t)^2 + \frac{1}{2}\cdot \int_{L_0}^{L} \rho \cdot \left(\frac{d}{dt}y(x,t) + x\cdot\theta(t)\right)^2 - EI\cdot\left(\frac{\partial^2}{\partial x^2}y(x,t)\right)^2 dx +$$
$$+\frac{1}{2}\cdot m\cdot\left(L\cdot\frac{d}{dt}\theta(t) + \frac{d}{dt}y(L,t)\right)^2 + \frac{1}{2}\cdot I_{tip}\cdot\left(\frac{d}{dt}\theta(t) + \frac{d}{dt}\frac{\partial}{\partial x}y(L,t)\right)^2,$$

Dynamics of such system is described by the partial differential equation (PDE) which can be simplified using Assumed Mode Method (AMM) – the ordinary differential equation (ODE). Deformations *y(x,t)* are expressed as:

$$y(x,t) = \sum_{i=1}^{n} \phi_i(x)\cdot q_i(t)\ ,$$

Where Φi(x) is approximating function:

$$\phi_j(x) = 1 - \cos\left(\frac{j\cdot\pi\cdot x}{L}\right) + \frac{1}{2}(-1)^{j+1}\left(\frac{j\cdot\pi\cdot x}{L}\right)^2.$$

Numerical simulations (4)

Taking into account that L is variable in time:

$$Lag = \frac{1}{2}\cdot I_{hub}\cdot \theta(t)^2 + \frac{1}{2}\cdot \int_{L_0}^{\boldsymbol{L(t)}} \rho\cdot\left(\frac{d}{dt}y(x,t) + x\cdot\theta(t)\right)^2 - EI\cdot\left(\frac{\partial^2}{\partial x^2}y(x,t)\right)^2 dx +$$

$$\frac{1}{2}\cdot m\cdot\left(\boldsymbol{\frac{d}{dt}L(t)} + L\cdot\frac{d}{dt}\theta(t) + \frac{d}{dt}y(L,t)\right)^2 + \frac{1}{2}\cdot I_{tip}\cdot\left(\frac{d}{dt}\theta(t) + \frac{d}{dt}\frac{\partial}{\partial x}y(L,t)\right)^2,$$

approximating function is modified:

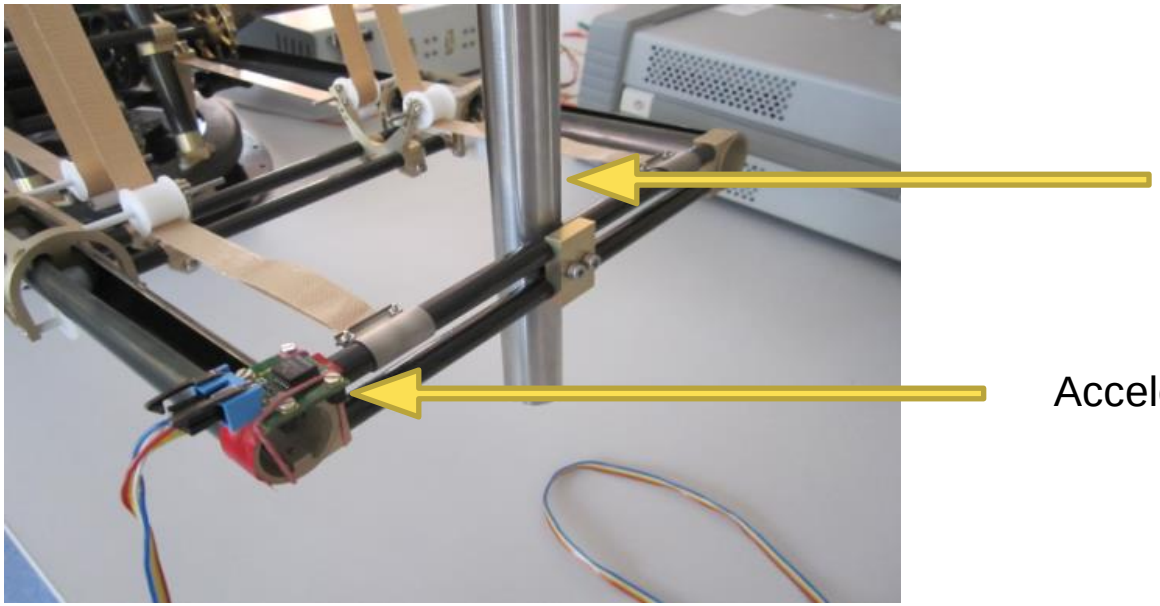
$$\phi_j = L(x,t)(t)\cdot\frac{1-\cos\left(\frac{j\cdot\pi\cdot x}{L}\right) + \frac{1}{2}(-1)^{j+1}\left(\frac{j\cdot\pi\cdot x}{L}\right)^2}{L_0}$$

The next step was to determine the attenuation coefficients of tubular manipulator arm.

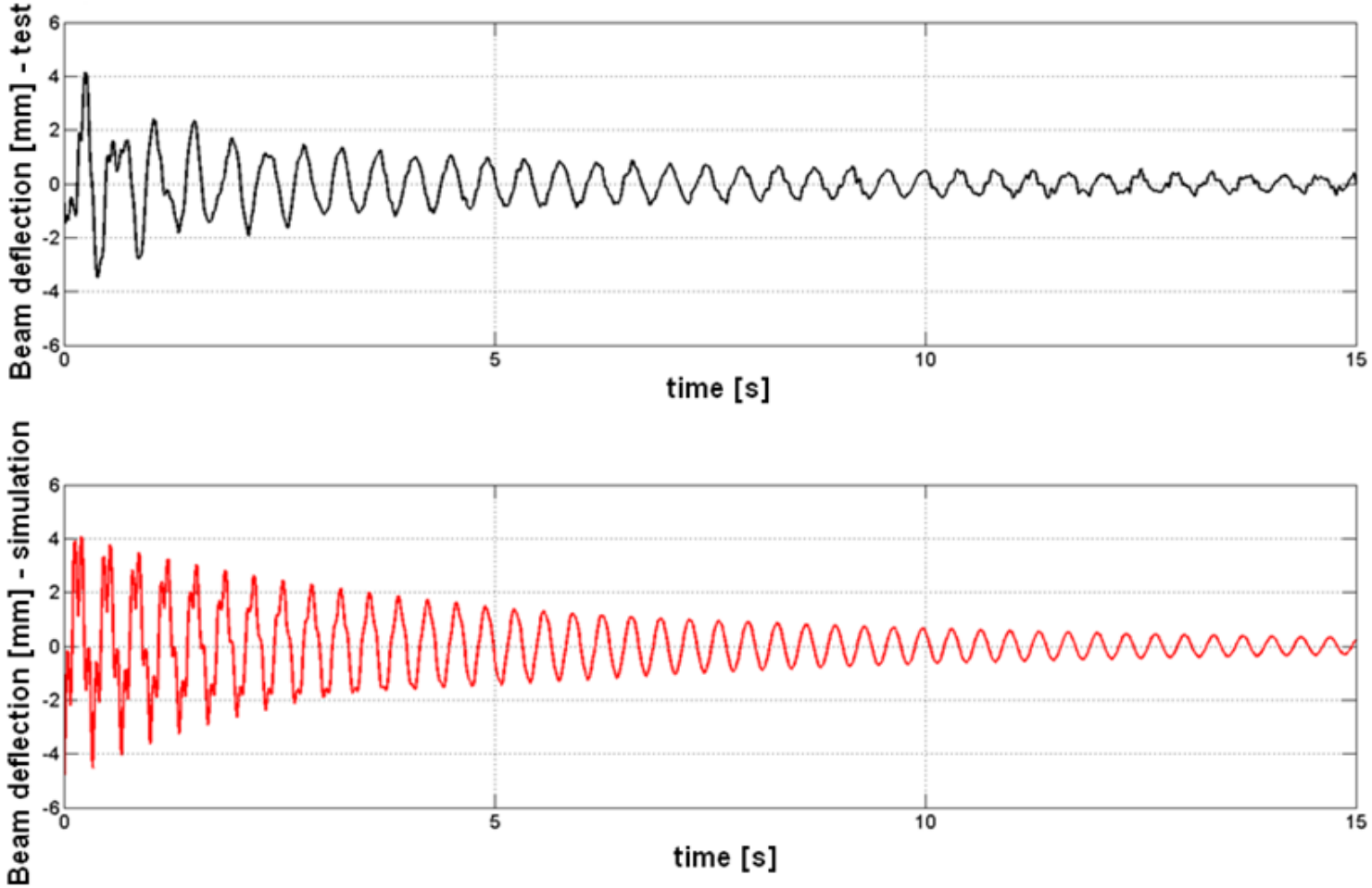
Prototype test supporting simulations

Dynamic characteristics of the manipulator was determined.

- Mass of 1kg simulating geological penetrator was attached to the end of manipulator arm,
- Natural frequency of manipulator arm was measured by MS9002 COLIBRYS accelerometer.

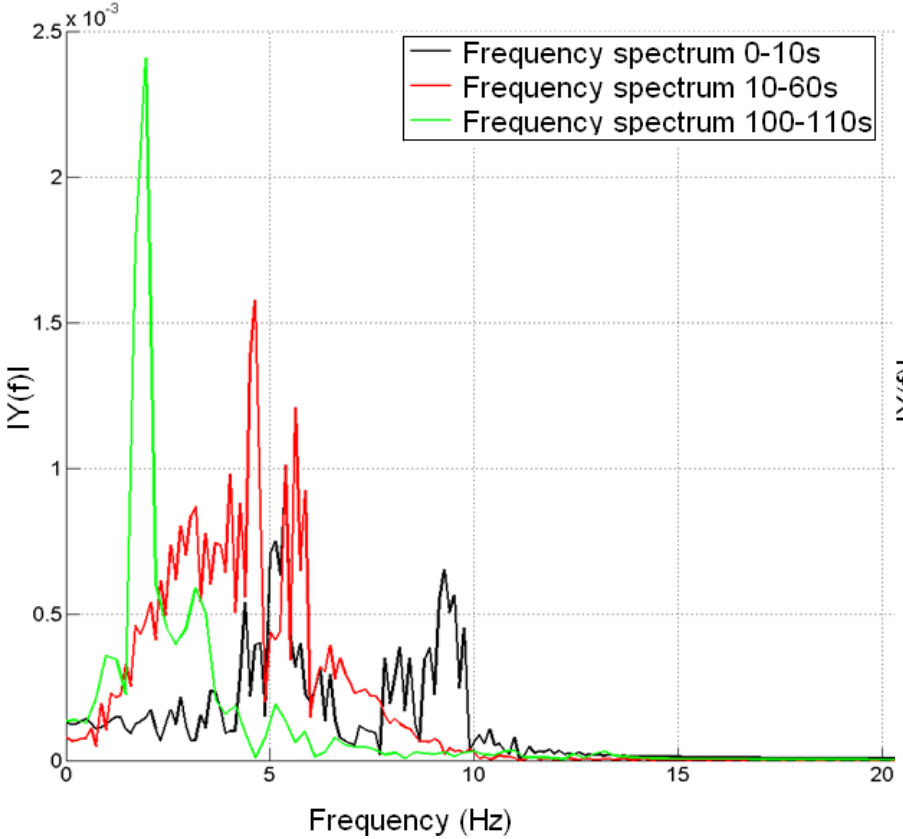


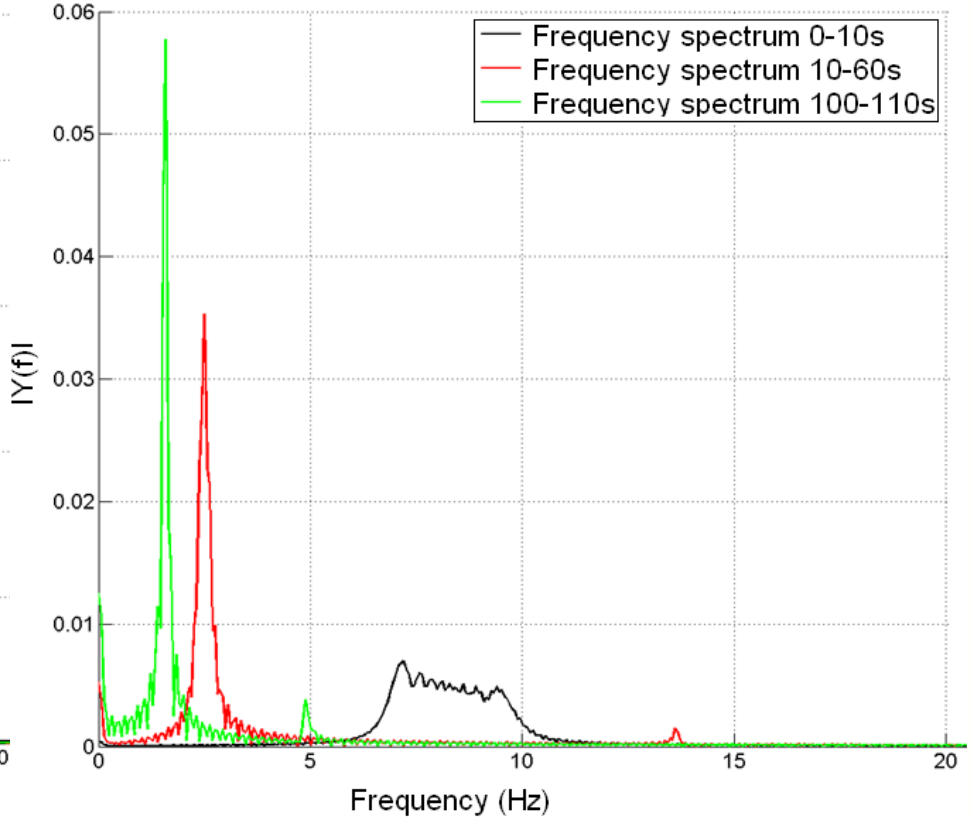
Simulations and tests results - comparison (1)



Vibration of manipulator tip after 5mm deflection (1.5m extension): test (top), simulation (bottom)

Simulations and tests results - comparison (2)

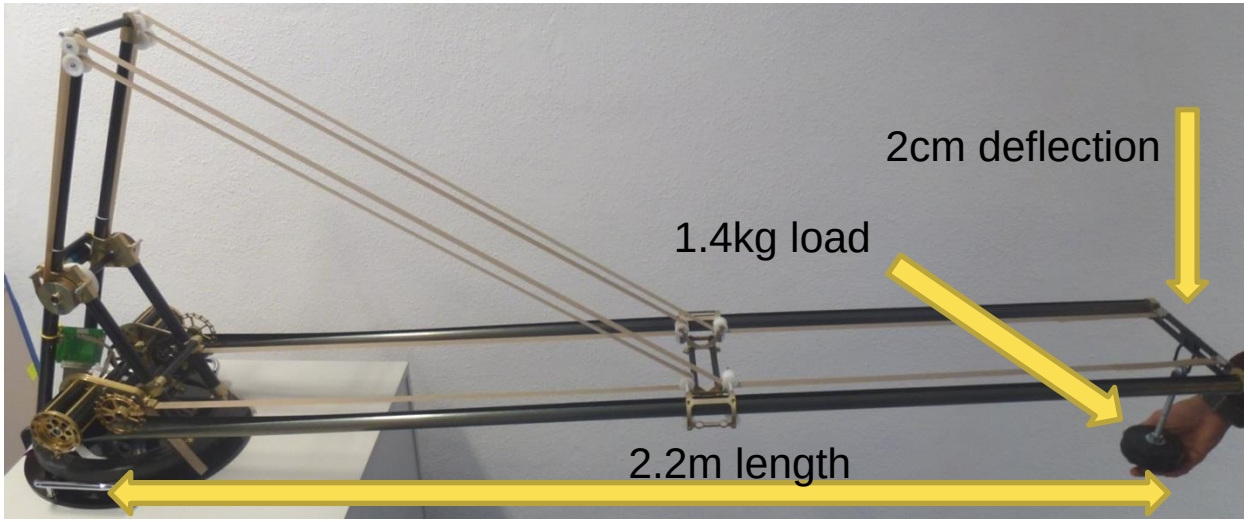




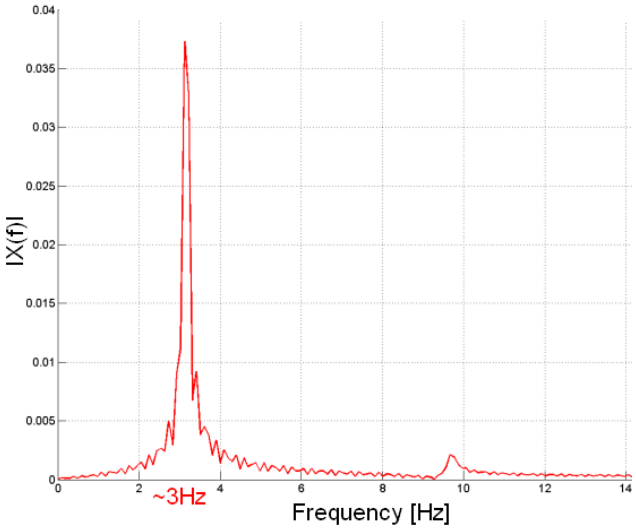
Frequency spectrum at selected stages of tubular arm extension: tests (left), simulations (right)

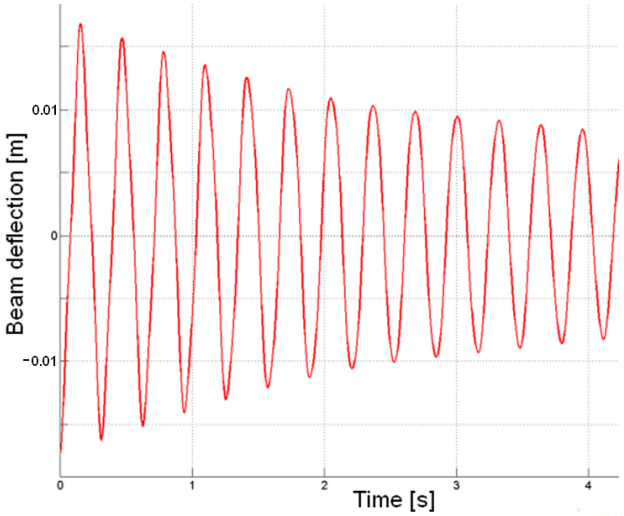
Simulations and tests results - comparison (3)

After **2cm** deflection of **2.2m** long manipulator arm loaded with **1.4kg** eigenfrequency was **~3 Hz** (test result).



The test result was confirmed by simulations





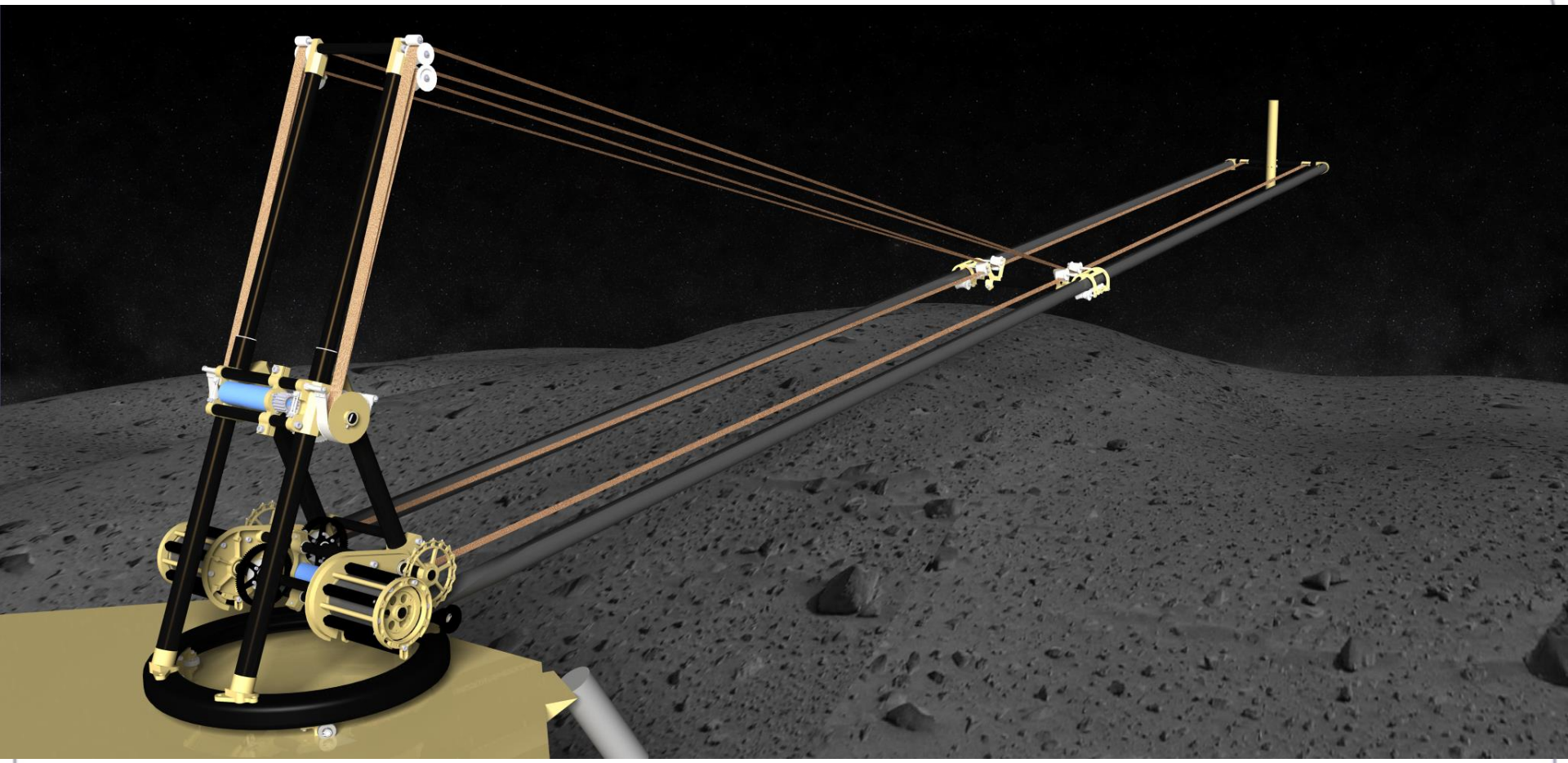
Performance

No.	Parameter	Result	Remarks
1	DoF	3	Extension, tilt, horizontal rotation
2	Mass	2.3 kg	Without the rotational joint
3	Dimensions	350x350x400 mm	Stowed configuration
4	Extension	3.2 m, 2cm/s	
5	Tilt	±30°	Velocity depends on extension
6	Rotation	±60°, 5°/s	
7	Loads	2kg on 2m distance (tested)	Planned 2-3kg on 3m distance
8	Stability	Withstands payload twisting by ±45° on 3m distance	
9	Eigenfrequency	~3 Hz	For 1.4kg on 2.2m distance

Conclusions

- Tests proved that ULPM can provide secure payload travel on a distance of 3m.
- Overall mass of 2.3 kg for the baseline construction (without the rotational joint) is close to required (2.0 kg in proposal).
- All conducted tests confirmed the functionality of the system.
- Prepared numerical model of ULMP is very complex but reliably reflects manipulator's dynamics.
- Simulation results coincide with conducted tests.
- Developed numerical model can be very helpful in preparing future control algorithm.

We have learned a lot about such a kind of manipulators ☺



thank you
for your attention