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


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INTRODUCTION

- SRC space mechanisms heritage

MUPUS Penetrator (on its way to comet 67P)

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

Mole Penetrator (2.2J, 0.5kg Tested up to 5m in Lunar regolith analogue)

CHOMIK Sampling Penetrator
MUPUS manipulator

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

PHILAE

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. Advantages: 3m range, 2-3kg
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:**
- \(\phi 6 \times 0.05 \text{ mm}, \) berilium bronze, \(8 \text{ g/m}, \) (under development in Poland)
- \(\phi 15 \times 0.10 \text{ mm}, \) stainless steel, \(34 \text{ g/m}, \) Ukrainian
- \(\phi 25 \times 0.15 \text{ mm}, \) stainless steel, \(90 \text{ g/m}, \) 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

Extension

Retraction
Guy support system

Functions:
- Increasing load capacity
- Lifting and lowering payload

Guy strips propulsion

Guy strip (teflon-coated aramid fibers)

Cart
TB
TBs end
- Guy support

ULPM DESIGN FEATURES

Guy support

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): 0.6 kg
- Size:
  - Diameter: 300 mm
  - Height: 45 mm
- Rotation speed: 1 rev/min
- Rotation range: ± 60°
- Maximum load capacity: 200N

ULPM DESIGN FEATURES

- Gear wheel with specially designed pins
- Brushless DC Motor with Encoder and Gearhead
- Rollers set
- Base plate
- Carbon fiber composite base ring
Functional test – 3DoF

ULTRA-LIGHT PLANETARY MANIPULATOR
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)
- 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
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,
- $\rho$ – tubular boom density.
Numerical simulations (3)

System Lagrangian:

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

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 \( \Phi_i(x) \) is approximating function:

\[
\phi_j(x) = 1 - \cos \left( \frac{j \cdot \pi \cdot x}{L} \right) + \frac{1}{2} (-1)^{j+1} \left( \frac{j \cdot \pi \cdot x}{L} \right)^2.
\]
Taking into account that \( L \) is variable in time:

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

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.
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 COLIBRY S accelerometer.

Prototype test supporting simulations

![Prototype test supporting simulations](image)
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)
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

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