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

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ABSTRACT

Planetary Manipulators are used quite often in space exploration and in situ measurement. Since it is planned to intensify space exploration (Mars and Moon are the mostly foreseen), its role should also expand [1, 7]. Presented in this paper is a newly developed 3dof Ultra-Light Planetary Manipulator (ULPM). Its main role is extended service for exploration tools and scientific instruments. The essence of the concept is taken from the MUPUS instrument manipulator for the Rosetta mission. In this attempt, it is successfully demonstrated that the previous concept was valuable and it could be a reference for a new, improved technology solutions. As result, an entirely new ULMP laboratory model was developed. The design is focused on the following constraints: low mass of the unit with possibly long extension range. The integrated device was intensively tested in laboratory conditions. The tests confirmed its operational functionality and overall performance. Particularly, it was ascertained that this very lightweight and flexible construction can safely operate with certain loads. The design of the Ultra-Light Planetary Manipulator was supported by appropriate analysis and dynamic simulations.

1. THE CONCEPT

Since 1996, CBK PAN has been involved in construction of various kinds of penetrators, including mole type devices, which are used for in situ measurements and/or collecting samples of the planets, moons and asteroids [8, 9]. All such devices are built to operate under ground surface, away from lander, in area free from shadowing and other disturbances. Therefore, there is a certain need to deploy the penetrators on a distance of 1-3m from the lander. For this purpose, an additional device (usually a manipulator) is required, which located on the lander board will be able to deploy and after that also support operation of a penetrator. A good example of such system is MUPUS device [2, 3], which right now is cruising to comet 67P/Churyumov–Gerasimenko on-board ESA Rosetta spacecraft. The MUPUS (shown in Figure 1) had significant influence on the concept of a new Ultra-Light Planetary Manipulator and, therefore, it is essential to approach closer its solutions.

Figure 1. MUPUS.

The MUPUS consists of two main mechanisms: the penetrator, dedicated for planet ground measurements (temperature profile, thermal conductivity, mechanical properties), and the manipulator, responsible for the delivery of the penetrator to the surface from the lander balcony.
Taking into account only the main technical features of the penetrator, the following should be highlighted:

- novel hammering electromagnetic drive with four power settings providing adjustment to the various ground mechanical properties,
- depth sensor indicating the depth progress of penetration,
- suitable for operation in very low temperatures and in microgravity environment,
- equipped with anchoring titanium tip.

Manipulator main functions include:

- penetrator deployment 1m away from the lander with tilting angle of 25°,

- insertion support, very important in the first initiation phase,
- depth progress measurement which is coupling with sensor on the penetrator rod,
- separation from the penetrator rod and retraction to the stowed configuration (lander can make free maneuvers).

The main elements of the manipulator are two parallel steel strips formed in a tubular shape (visible in Figure 2), which are rolled up on the reels when stowed. The extension is provided by the stepper motor which unwinds the strips.

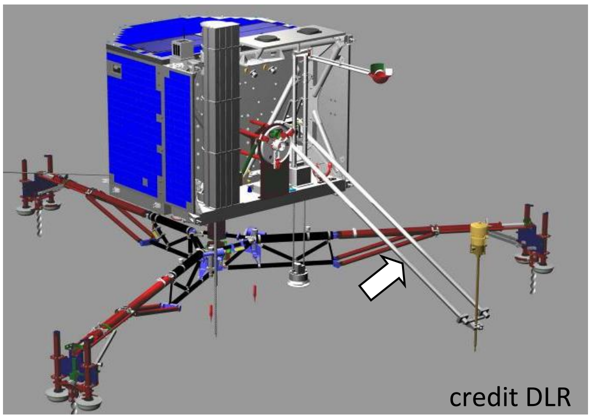

Figure 2. MUPUS Penetrator deployed by the tubular boom manipulator (marked by arrow) from the Philae lander.

Figure 3 shows a dedicated part of the whole device containing two parallel tubular booms (TB).

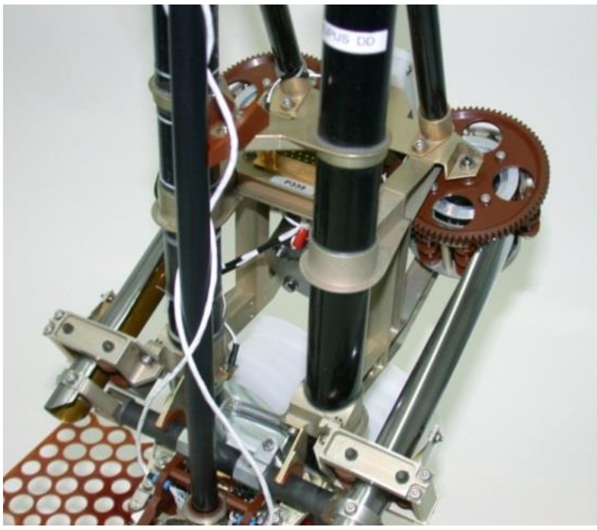

Figure 3. MUPUS manipulator in stowed configuration. Two parallel booms were arrayed on distance of 120mm, rolled up on two reels and guided by the front rollers.

As an effective extension of the presented MUPUS instrument, the idea for Ultra-Light Planetary Manipulator (ULPM) was arisen. According to the conception, the mechanism should have three degrees of freedom (3dof): extension (and retraction), tilt up and down, and horizontal rotation. Its main advantages include long range of extension – about 3m and relatively low weight – about 2kg. The images below explain the principle of operation of the Ultra-Light Planetary Manipulator. Figure 4 shows the ULPM in stowed configuration.

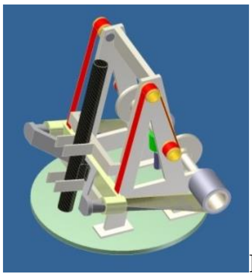

Figure 4. Manipulator stowed.

Figure 5 presents the ULPM conceptual system where the tubular booms are supported by the guy strips. An exploration tool, e.g., mole penetrator is gripped by the end effector.

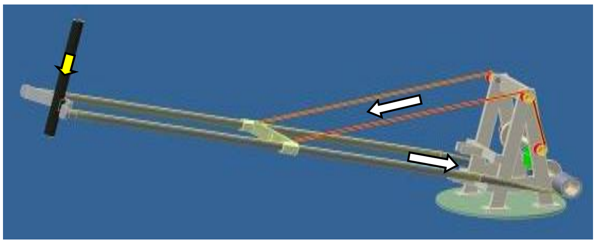

Figure 5. ULPM during operation. Arrows demonstrate that the guy strips are axially tensioned and the tubular booms are axially compressed in the indicated area.

Figure 6 shows the full length extension and lowering of the payload to the ground.

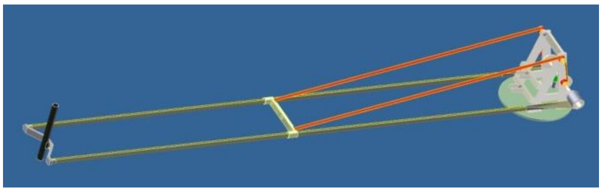

Figure 6. Maximum length of deployment. The tool is able to touch the ground.

2. DESIGN FEATURES

Figure 7 shows the general view of ULPM prototype with its main parts; among them are TB and the driving mechanism used for their extension. The next important unit is the guy support system with the drive provided for lifting and lowering the payload. The whole structure is attached to the rotational joint mechanism.

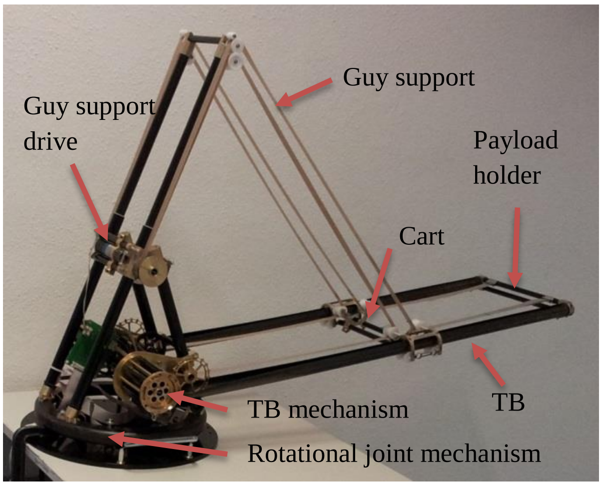

Figure 7. Ultra-Light Planetary Manipulator.

The major advantages of TB are easy and dense storage, which makes possibility to pack meters of TB in compact size, and high flexural stiffness. CBK PAN has many years of experience with mechanisms using tubular booms, e.g., three antennas deployments with TRL 9. Therefore a number of problems concerning TB bad properties has been solved in the past. One of them was poor torsional stiffness of a single boom. To handle this problem, two parallel booms were used. Each of TB is made of stainless steel and has 25 mm diameter and 0.15 mm thickness. These tapes sizes with supporting guy strips ensure that the device will be able to transfer desired loads.

TBs are propelled by two counter-rotating electrical DC gear-motors. The first one transfers the power by spur-gear to extension drive wheel which has specially designed pins inserted on its circle. Pins cooperate with holes drilled in TB. During wheels rotation, two TBs move forward. Coupling of them with the meshed pins provides that the length of both TBs is correlated and accurate.

For retracting of TBs the second motor is used which drives the reels designated to roll up the strip. In Figure 8 it is shown exactly which parts are involved for forward and backward motion.

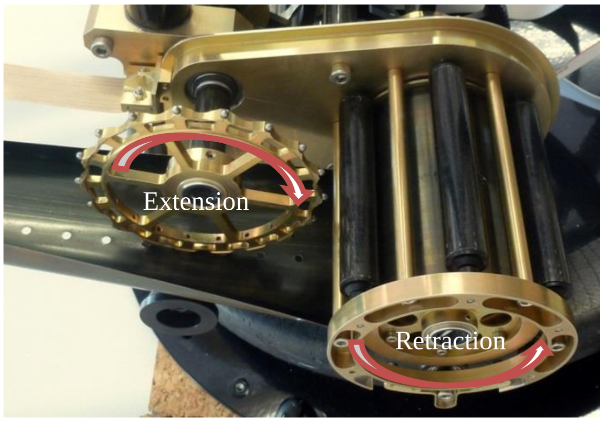

Figure 8. Translation motion drive which is based on meshing of the TBs holes with the pins toothed wheel.

On both sides of the manipulator two pairs of guy strips have been applied (Figure 9). Those strips main support functions are to increase a maximum load capacity of the whole device and to lift and to lower the payload. Through specially designed set of rollers and clampings, guy strips maintain the cart in a proper position. Thanks to that kind of solution, the cart and the guy strips are holding up TBs in their middle, independently of their ends positions. This was devised as an optimum to carry the maximum loads.

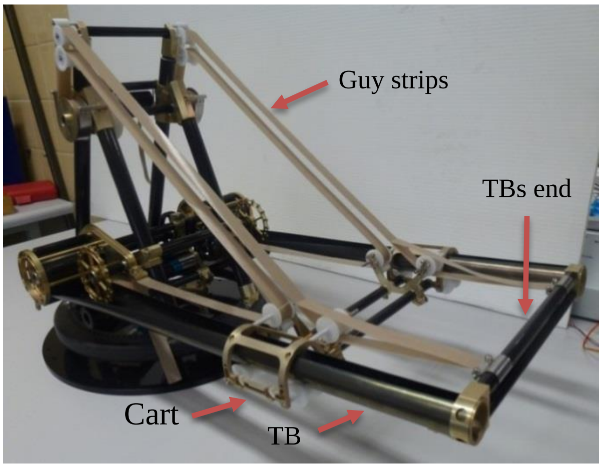

Figure 9. Guy strips subsystem.

The device is equipped with a special kind of deployable structure (Figure 10). In stowed configuration, ULPM has 350mm of height. The biggest advantage of the deployable mechanism is its ability to gain additional 250mm in height. It makes it possible to have a wider support angle - a more optimal solution for such long, end-loaded boom. At the same time, the stowed configuration is compact and takes up little of space. Almost the whole structure is composed of CFRP tubes.

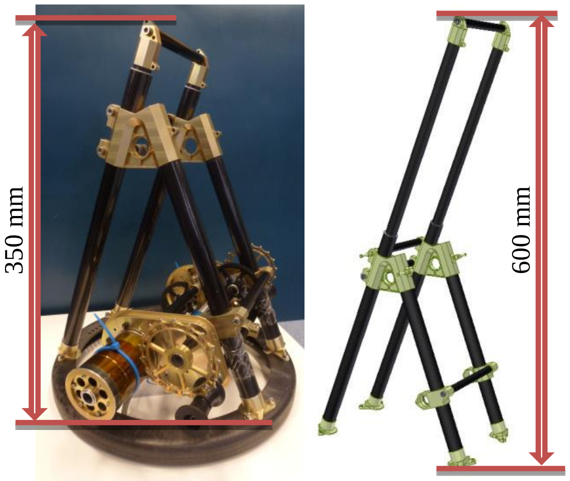

Figure 10. ULPM deployable structure

An optional equipment is the rotational joint mechanism presented in Figure 11. It gives one additional, third dof, which makes the ULPM a more universal device for extra demanding applications, but it is also heavier by about 600 grams. Rotational joint mechanism consists of carbon fiber composite base ring. Thanks to the carbon fiber and a special construction, the base ring has high mechanical strength and, moreover, it is very light. It has three sets of supporting rollers. The principle of drive is similar to the TB extension mechanism. The gear wheel with special designed pins cooperating with holes drilled in base plate were used.

Figure 11. Rotational joint mechanism fixed on the baseplate. The ring can withstand 300N loads.

3. CONDUCTED TESTS

In CBK PAN the following tests were carried out to verify and confirm the functionality of the system:

- Kinematic test – it confirmed that the device is able to extend to 3 m long, tilted between angles +30°, –15°and horizontally rotate between ± 60°.
- Load test in Earth gravity – the test proved that the mechanism is able to extend for 2.2m with 1.4 kg mass fixed on its end (it corresponds to about 8 kg on the Moon).

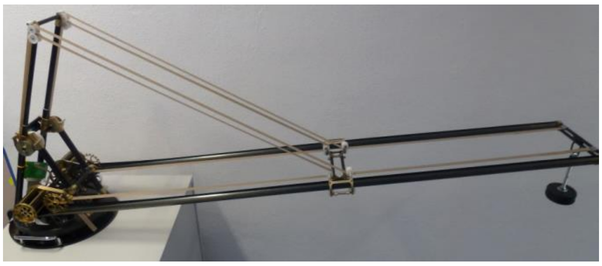

Figure 12.Prototype of the ULMP with 1.4kg load during tests.

- Stability and eigenfrequency test (Figure 12) - after 45deg torsional deflection, mechanism quickly gets back to the state of equilibrium. Eigenfrequency has been estimated at about 3Hz with 2.2m TB extension and 1.4kg load on the TB end. Naturally, the value of eigenfrequency depends on load and extension length of TBs.
- Load test in simulated low gravity conditions (Figure 13) - for 2, 3, 4 and 5 kg load the action of full extension (3m) and retraction was performed in simulated conditions (set up to the moon gravity). The test confirmed that construction of the manipulator is adapted to the certain loads.

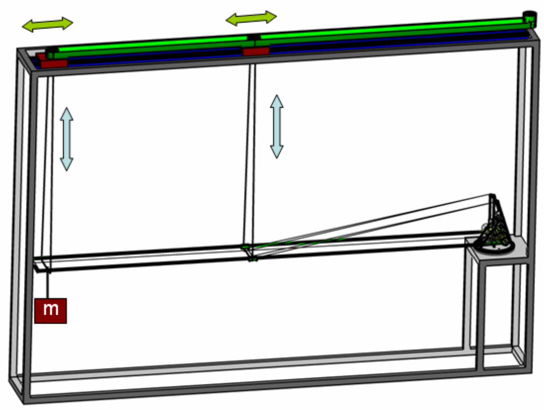

Figure 13. ULPM test bed with simulated low gravity conditions. Two motors on the upper beam through the strings provided appropriate reduction of the gravity load.

4. SIMULATIONS AND ANALYSIS

On the simulation level, ULPM was described as a serial manipulator which consists of three kinematic pairs: two rotational and one translational. Kinematic scheme of the manipulator is presented in Figure 14.

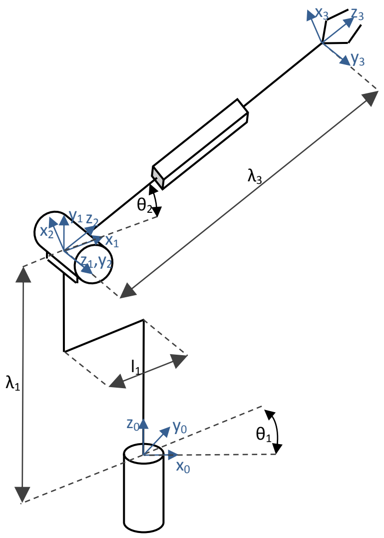

Figure 14. Kinematic scheme of the manipulator.

In principle, the manipulator includes flexible shape and, therefore, the Dynamics of such system is described by the partial differentia equation (PDE) which can be simplified using assumed mode method – the ordinary differential equation (ODE) [5].

$$\begin{gathered}[M_{rr}(q_r,q_e)]\{\ddot{q}_r\}+[M_{re}(q_r,q_e)]\{\ddot{q}_e\}+\\ \{h_r(q_r,q_e,\dot{q}_r,\dot{q}_e)\}=\{\tau\},\\ \\ [M_{er}(q_r,q_e)]\{\ddot{q}_r\}+[M_{ee}(q_r,q_e)]\{\ddot{q}_e\}+\\ [K_e]\{q_e\}+\{h_e(q_r,q_e,\dot{q}_r,\dot{q}_e)\}=\{0\},\end{gathered} \tag{1}$$

where M is mass matrix, q_r and q_e are rigid and elastic elements of state vector respectively, Key is stiffness matrix and hr vector which include coriollis therm. The external torque is described by τ. Nevertheless, for determination of the level of torque appearing during typical manipulator operation, the standard multi-body approach [4] for rigid bodies was taken into account and the elastic term in Eq. 1 was neglected.
To solve these equations, the simulation tool was developed at the SRC PAS based on SimMechanics software (part of the MATLAB Simulink) [10]. The use of this platform allows incorporating in one environment all the elements essential in numerical simulations of the manipulator dynamics [6]. The detailed model of the first rotational joint of the manipulator is presented in Figure 15.

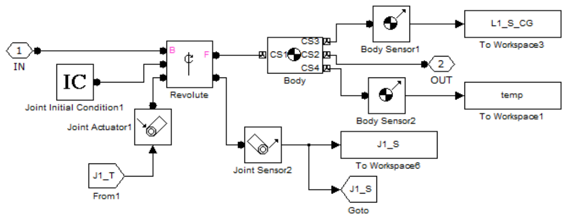

Figure 15. Simulink model of manipulator first joint.

5. CONCLUSIONS

To summarize, the developed manipulator has 3 dof - extension, tilt, horizontal rotation, and a mass of 2.3 kg. Without the rotational joint, the dimensions are 350x350x400 mm in stowed configuration. The maximum extension length is 3.2 m with extension speed of 2 cm/s. The tilt angle is contained between +/- 30° and the velocity depends on the extension. The rotation angle is between +/- 60° with the rotation speed of 5/s. The maximum tested load was 2kg with 2m extension and 5 kg with 3m extension in simulated microgravity conditions. The stability test indicated that after 45 deg deflection, the mechanism quickly gets back to the state of equilibrium. Eigenfrequency has been estimated at about 3Hz with 2.2m TB extension and 1.3kg load on the TB end.
The attained properties for the ultra-light planetary manipulator are given below.

Parameter	**Result**
Envelope (stowed) LxWxH	350x350x400mm
Mass with (without) rotational joint	2.7 kg (2.1 kg)
Deployment length	3.0 m
Deployment speed	0.25 – 1.0 m/min
Tool mass with end-effector	Depends on extension and gravity: 1.4 – 10 kg
Power consumption	2.0 – 3.0W
Tiltingangle	+30° – -15°
Horizontal (azimuth) turn	±60°
Stability	Withstands payload twisting by ±45° on 3m distance
Eigenfrequency	~3 Hz - for 1.3kg on 2.2m distance

Table 1. Properties of the Ultra-Light Planetary Manipulator

6. ACKNOWLEDGMETS

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