# DEPLOYMENT BOOM CONCEPTS FOR THE POSITIONING OF SCIENTIFIC INSTRUMENTS ON PLANETARY SURFACES

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## ABSTRACT

The in-situ exploration of planetary surfaces by lander vehicles requires in most cases suited deployment tools which can mechanically release the involved instruments from their stowed configuration and bring them into their desired operating position beside or above the lander platform. The concepts described in this paper refer to a multi-link deployment boom which can solve this task with minimum complexity but maximum reliability. This boom was particularly designed for soil-oriented instruments. Each of its links consists of an ultralight carbonfiber structure combined with a redundant electrical drive in the axes which is simple but efficient. The boom can climb across various obstacles while it rolls away from the lander and simultaneously unfolds itself. Analyses, simulations, and tests have shown that the multi-link unfoldable deployment boom is a promising tool for planetary exploration missions.

## 1 INTRODUCTION

The scientific exploration of the Solar System needs both orbiters which observe planets and moons from a global overview position in space, and lander vehicles which land on the surface of the investigated body for detailed local measurements, photographs, and operations on the soil.

Such lander vehicles need to be equipped with suited deployment tools for various sensors and instruments, since most of the scientific measurements and operations cannot be performed directly inside the lander. For instance, cameras and sensors for atmospheric measurements (wind, temperature, pressure, etc.) must be erected above the lander platform up to a certain height, as well as antennas which secure the telecommunication after landing. Other instruments need direct access to the planetary soil, such as seismometers, moles, soil humidity sensors, magnetometers, drills, and tools for sample collection. If the lander mission is based on landing shock absorption by means of an airbag, then the deflated airbag will after landing most probably lie between the lander bottom and the planetary surface like a blanket, thus forming an additional obstacle with undefined edges.

The development of suited deployment booms is therefore a key task for successful planetary lander missions. Such deployment booms shall be as lightweight and simple as possible, stowable in a very small volume, and they shall reliably function even under unforeseen geometrical circumstances (as tilted ground, disadvantageous position and size of stones, creases of a deflated airbag, etc.). Of course a fully computer-controlled robotic arm could easily meet almost all mechanical challenges. But it would neither be small, nor simple, nor particularly lightweight. Rather, it would require a large amount of electronic and software equipment that would be exaggerated by far, because the instruments shall be positioned only once, on a single occasion. Consequently, robotic arms were kept out of the following considerations.

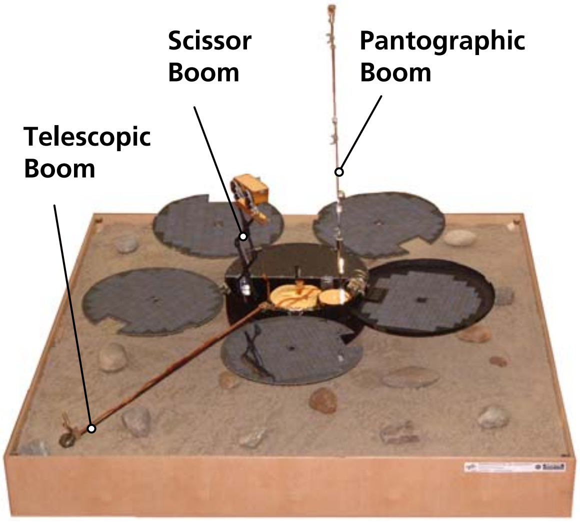

Fig. 1. Three alternative boom types for deployment only above the lander, resp. “through the air”

Fig. 1 shows three alternative deployment booms developed for instruments on the previously planned CNES-DLR-FMI mission "NetLander". Two of them were bound for vertical deployment, i.e. for instrument positions above the lander platform, namely a scissor boom for the erection of a panoramic camera, and a pantographic boom consisting of rigid links and spring-driven hinges for the positioning of some atmospheric sensors in a satisfying height above ground. For any horizontal deployment of instruments in parallel to the surface, however, these solutions would have been unsuitable: Already the first obstacle, for instance a stone, could become a showstopper, because neither the scissor boom nor the pantographic boom could evade it. The third option depicted in Fig. 1, the telescopic boom, can only overcome obstacles if it is swung around its root hinge in a rampant and then rising arch while it unfolds itself. Indeed this concept was used for the small and light NetLander magnetometer sensor depicted in Fig. 1. But for all instruments that are too large or too heavy to be swung "through the air" the situation is similar to the first two cases. Summarizing one can say that soil-oriented instruments of a certain size which must be moved radially away from the lander platform need a new type of deployment boom.

## 2 THE CHALLENGE ARISING FROM HP3

The challenge to develop the above-mentioned new type of deployment boom arose from the participation of the DLR Institute of Composite Structures and Adaptive Systems in the proposals for a geophysical instrument package on the ESA mission ExoMars [1]. In particular, the instrument HP3 that had been proposed for the ExoMars mission needed certain landing site requirements to be fulfilled [2] and a suited deployment tool to be at hand. Although this mission option (HP3 on ExoMars) did finally not come true, the task of developing a horizontally moving deployment tool with minimum complexity, that could overcome various obstacles, remained a challenging open issue.

### 2.1 Heritage from Mars-96

In the 1990´s scientists from the Martin Pfeil TRAWID company in Hildesheim (Germany), from the Technical University of Braunschweig, and from DLR had collectively developed a deployment boom for the magnetometer on the Russian Mars-96 mission (see Fig. 2). The basic idea of this boom was the consecutive uncoiling of its links, leading to a propagation in radial direction away from the lander. This boom could easily climb across obstacles and properly function on tilted ground. In any case the magnetometer at the tip would finally achieve a well-defined stable attitude on the ground with a rigid reference to the lander coordinate system (as it is mandatory for measurements in a vector field). Since the magnetometer was small, the drives of the links were torsional springs, and their consecutive unlocking and unrolling was controlled by a suited mechanism.

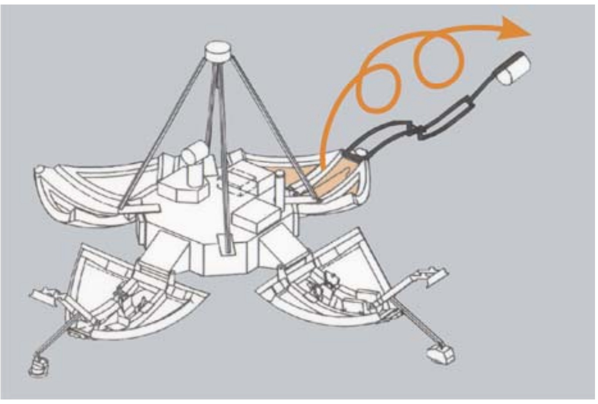

Fig. 2. Useful heritage: Mag-boom for Mars-96 [3]

For the envisaged deployment of the HP3 instrument from the ExoMars lander platform it became clear that the Mag-boom designed for Mars-96 would be a useful heritage, but that the drives could no longer be springs: The mass to be moved was now much larger, the distance to be bridged was longer (requirement: 3 m), and the number of links needed to reach this distance would certainly be larger than three. Concepts for a safe, simple, and redundant motor drive were needed.

### 2.2 Approach for HP3

The admissible envelope length of the stowed boom on the ExoMars lander was in the range of 400 mm (slightly varying and always under negotiation during the progressing ExoMars development). This constraint led to a minimum number of 7-8 links in order to achieve the required 3000 mm deployment distance.

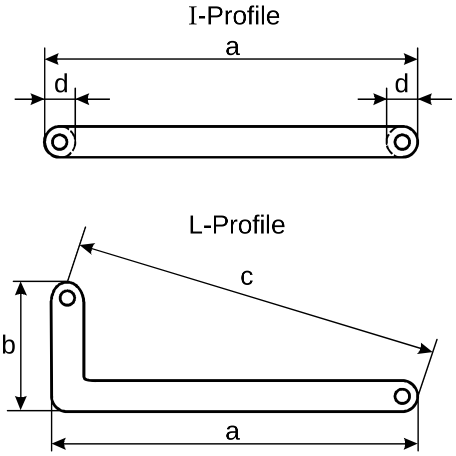

Fig. 3. I-profile versus L-profile of the links

However, if the links are consecutively nested, and their geometry is simply longitudinal (I-profile), then each link is by $2d$ shorter than the previous one:

$$a_{n+1} = a_n - 2d \tag{1}$$

This incremental length loss is due to the presence of the axes (in transverse direction). Since $d$ must be in the range of (at least) 20-30 mm in order to allow for motor and gearbox accommodation inside the axis tubes and to ensure sufficient mechanical stiffness, it is evident that, with the initial constraint of $a_1 \approx 400$ mm, the total boom length converges at a too low value. The only way out is the replacement of the simple longitudinal links (I-profile) by links with an L-profile, so that the axes can be stacked above each other, instead of being nested into one another (Fig. 4).

Fig. 4. Boom links in stowed configuration (still without mechanisms, and locked with aluminium clamps)

The height of a stack with $n$ links is at least $n \cdot d$ so that, under the assumptions made here, 200 mm are a realistic value. The width depends on the dimensions of the deployable payload unit that is enclosed within the two flanks of the innermost link. In the present case, the value of 350 mm resulted from the dimensions of the HP3 instrument box. Also the mass assumption for the payload unit (approx. 2500 g) was derived from HP3.

Tab. 1. Representative boom requirements (derived from HP3 on ExoMars)

| Requirement | | Value |
|---|---|---|
| Length | (stowed configuration) | 400 / 433 mm |
| Width | ( “ “ ) | 350 mm |
| Height | ( “ “ ) | 200 mm |
| Mass of the deployed instrument | | ≤ 2500 g |
| Deployment distance | | 3000 mm |

Fig. 5 illustrates the consecutive unfolding of such a boom out of the lander platform across one of the unfolded petals and the edge of the deflated airbag onto the planetary soil.

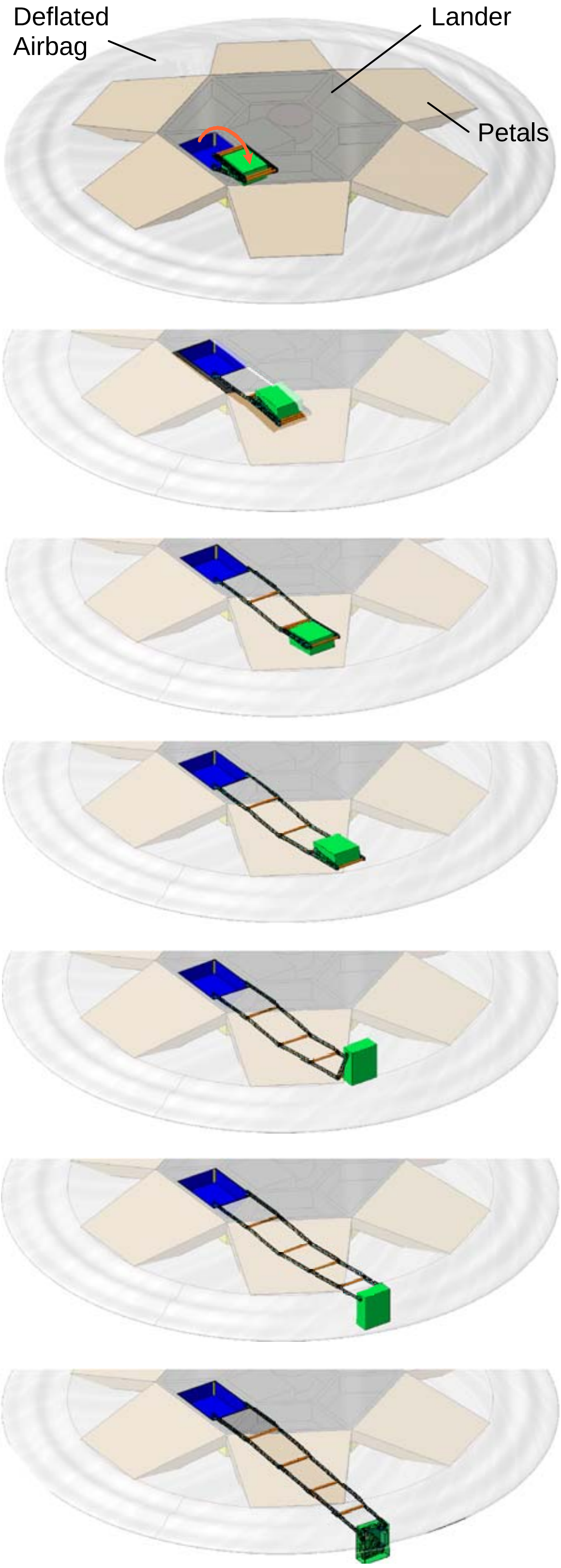

Fig. 5. Unfolding scheme of a boom for soil-oriented instruments, originally developed for HP3

## 3 BOOM DESIGN

### 3.1 Stiffness and Stability

The boom links are designed as pairs of ultra-light carbonfiber sandwich L-profiles with carbonfiber tubes as axes in between these profiles. The sandwich face sheets consist of two layers of high-modulus M40J fabric and are 0.5 mm thick. The core is an aluminium honeycomb (Aeroweb 1.4-5052-007) of 4 mm thickness, so that each L-profile is in total 5 mm thick. The profiles are circumferentially reinforced by a unidirectional M40J roving surrounding the sandwich core edge.

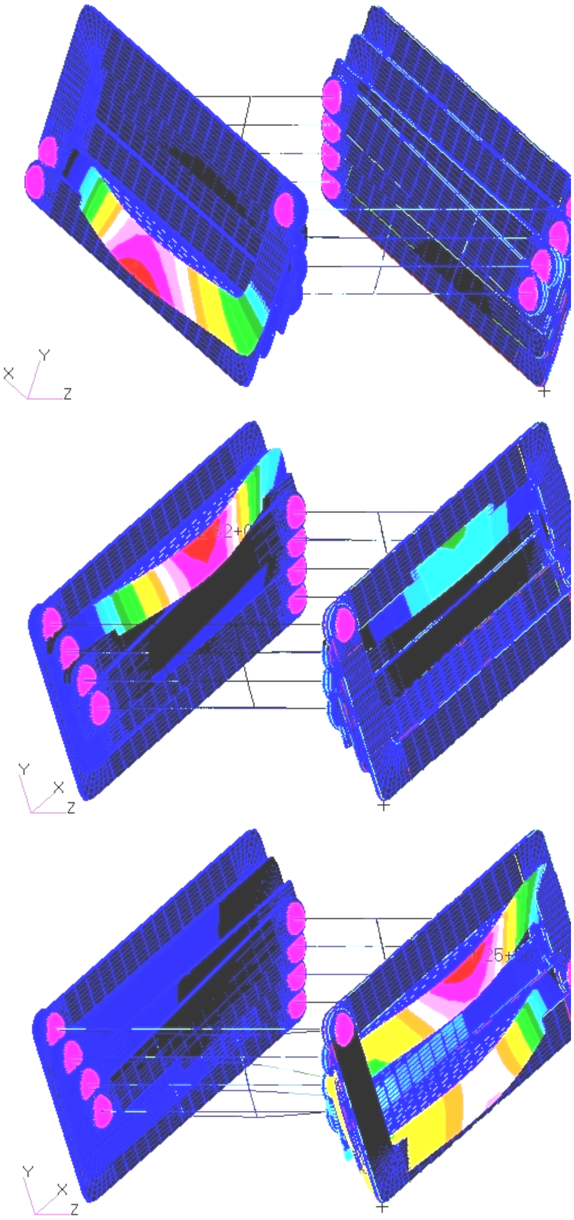

Fig. 6. Eigenfrequencies of the stowed configuration at 152, 169, and 177 Hz

The low weight and high stiffness of this structural concept leads to excellent mechanical properties. The structural mass of the boom links (without mechanisms) is in the range of 70-90 grams, slightly varying with the individual geometry.

This structure, namely in its stowed configuration (see Fig. 6), was thoroughly analyzed by one of us (Bendel) by means of a PATRAN / NASTRAN model. Realistic fixation on a rigid base by launch locks was assumed.

The quasistatic analysis with 43.3 g acting in the main load direction (alternating between x, y, and z), and with ±8 g simultaneously acting in the respective two transverse directions, showed that all deflections remain uncritically small. In the next step, the modal analysis gave evidence that the first global eigenfrequency (with more than 10% of the mass involved) is beyond 150 Hz, which is a realistic criterion for vibrational loads during launch [4]. The frequency responses under harmonic excitation were also determined.

Shaker tests for further verification are planned for the near future, but already now it is sure that the stowed configuration can safely withstand the usual vibration loads on a launcher.

In the deployed configuration, on the other hand, the boom must keep its stability (i.e. its stable attitude) even if the payload instrument induces mechanical loads. In case of the HP3 instrument for ExoMars this was particularly relevant because a mole was hammering on the surface in order to penetrate into the ground, and the rebounds had to be absorbed by the boom. A special outdoor test (Fig. 7) on sandy ground proved that any movements (or even hopping) of the boom tip could be excluded.

Fig. 7. Stability test in deployed configuration with hammering instrument device

The consecutive unwinding of the boom links is a steady parallel repetition of a single DOF, namely rotation around an axis transverse to the propagation direction. It is mandatory that this process runs only forward, no matter which kind of drive is installed, because otherwise no stable final attitude is possible. Consequently, all axes are equipped with freewheels which block any backward motion at once.

## 3.2 Drive Concepts

There are two basic options for the electric drive of the deployment boom:

Option 1: There is a single motor (with a gearbox and a winch) at the root of the boom which acts on all boom links by means of a long rope (e.g. a Dyneema string) and suited deflection pulleys. Provided that the consecutive release of the individual links is mechanically controlled by suited spigots, this concept can in principle work well.

Option 2: There are individual motors in each of the axes, and each motor has its own gearbox to achieve the necessary torque. The control (i.e. motor power on/off) is performed by switches which are mechanically triggered at a certain opening angle.

A thorough evaluation of the mechanical "pro´s" and "con´s" of both concepts has been performed by one of us (Leipold). The main advantage of Option 1 is certainly that only a single motor is needed (or two, if it shall be redundant). On the other hand, the envisaged mass for the payload instrument that shall be deployed (up to 2.5 kg) leads to a necessary torque of 3.6 Nm for the first link, and still 1.9 Nm for the last one. The deflection pulleys need then to have a large diameter in order to achieve the necessary gear reduction in relation to the winch, so that they can be hardly accommodated in the admissible envelope. Moreover, the unwinding of each link must be mechanically blocked at 180° opening angle because otherwise the continuous tension in the rope would contract the links towards the other side. This blocking mechanism must be quite strong, since the tensile force in the rope is in the range of 100-200 N.

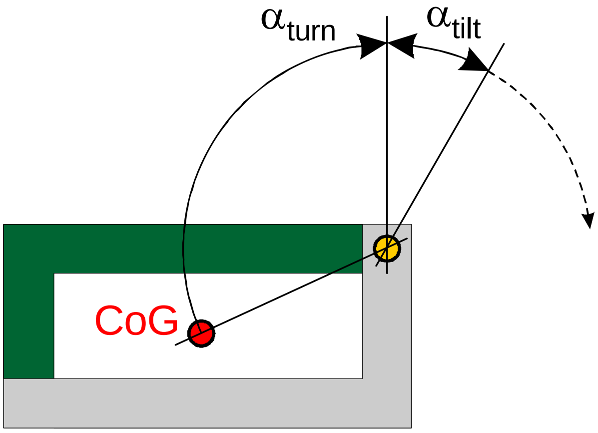

Fig. 8. Driven and free rotation in Option 2

Option 2 needs at least one motor (with gearbox) for each individual axis. However, in order to avoid single point failures upon unfolding, the motors shall be redundant, so that a complete boom with 7 or 8 driven axes needs 14 or 16 motors, respectively, which is certainly a lot. On the other hand, the individual drive can better react on obstacles and on locally curved ground. As shown in Fig. 8, the driven angle consists of two components: the first is the angle between the CoG of the "package" that must be turned over and must therefore cross the vertical line, and the second shall make sure that this works even uphill on tilted ground with a tilt angle of 30°. The striking advantage is that subsequently, when the motor has been switched off, the rotation can continue freely (only driven by the local gravity) until the boom hits upon the ground or upon an obstacle. Since any backward motion is immediately blocked (see above), a very stable attitude is achieved which is well adapted to the local contour.

Option 2 was therefore regarded as the obvious solution, until it became clear that the necessary gear reduction between small motors embedded in the axes and rotations of the full "boom package" with 3.6 Nm cannot be achieved by a small planetary gearbox alone.

Fig. 9. Motor, gearbox, and winch embedded in the axis (carbonfiber cover removed)

The final solution is therefore a hybrid one, as depicted in Fig. 9, and as recommended in [5]: The axes are individually driven (as in Option 2), but the gearbox adapted to the motor does not act directly on the following boom link. In order to achieve the necessary torques, i.e. the necessary additional gear reduction, ropes are used (as in Option 1), but each rope only from one link to the next one. On the driving side, the rope is spooled on the extended gearbox axis between two washers which serve for proper alignment. On the driven side, it acts on the curved outer edge of the L-profile of the following boom link, which has a much larger radius (see Fig. 10). For better guidance, the carbonfiber L-profiles have gotten a chamfer at this edge. The selected motors are brushless DC motors from *maxon* (type EC 13) with directly adapted planetary gearboxes type GP13A.

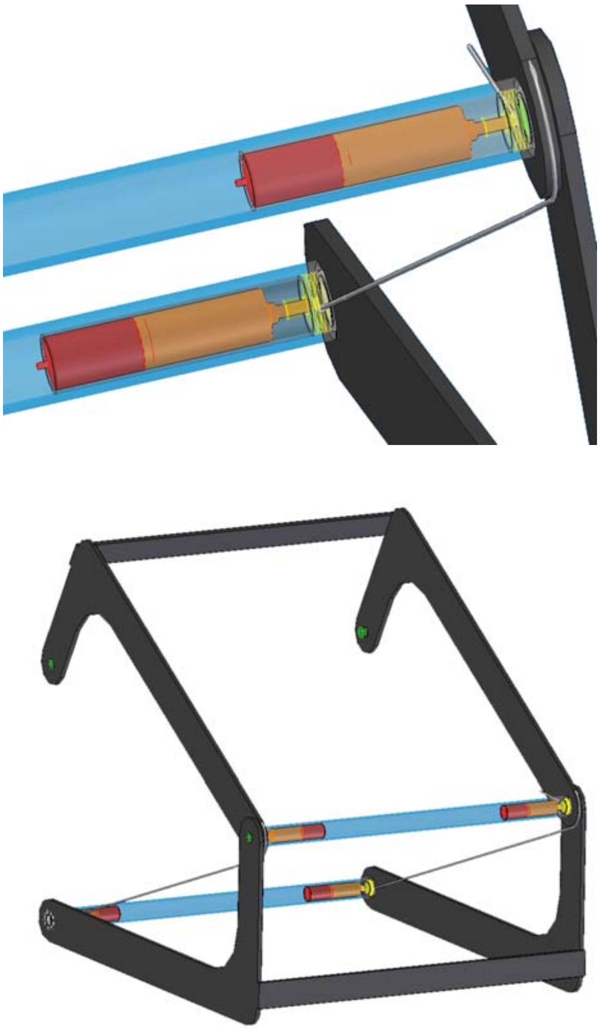

Fig. 10. Hybrid drive concept

### 3.3 Control Circuitry

The deployment is simply initiated by switching the motor power supply on. The on/off sequences of the individual motors are controlled (1) by switches that are triggered mechanically when a certain opening angle has been achieved, and (2) by time-out switches.

## 4 KINEMATIC STUDY

One of us (Junghans) has investigated the kinematic behaviour of the unfolding deployment boom in detail. The tool used for this investigation was the ADAMS software (= Automatic Dynamic Analysis of Mechanical Systems) from MSC. Apart from the geometrical and mechanical properties of the moving body itself, ADAMS takes also environmental properties into account, for instance the local gravity, tilt angles, and the presence and location of obstacles (see the example in Fig. 11). The present study assumed (1) the above-described boom structure, (2) the hybrid drive option with 200 g mass for the drive in each axis, (3) an instrument mass of 2.5 kg, and the following scenarios:

Tab.2. Scenarios simulated with ADAMS

| Scenario | Motion both across petal and between petals |
|---|---|
| 1 | Tilted ground 30°, uphill |
| 2 | Horizontal plane without obstacles |
| 3 | Horizontal plane with close obstacle |
| 4 | Horizontal plane with distant obstacle |
| 5 | Horizontal plane with close & distant obstacle |

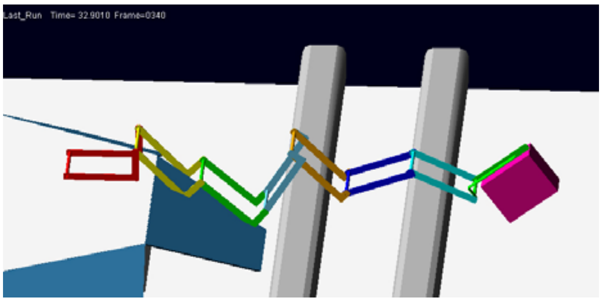

Fig. 11. Scenario 5 simulated with ADAMS

As shown in Fig. 12, the presence of an additional obstacle on a horizontal plane does not affect the achievable final deployment distance very much, which is an encouraging result. The boom turns out to be extremely versatile.

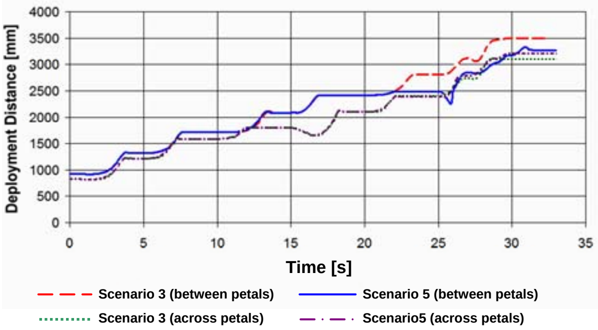

Fig. 12. Deployment distance for different scenarios

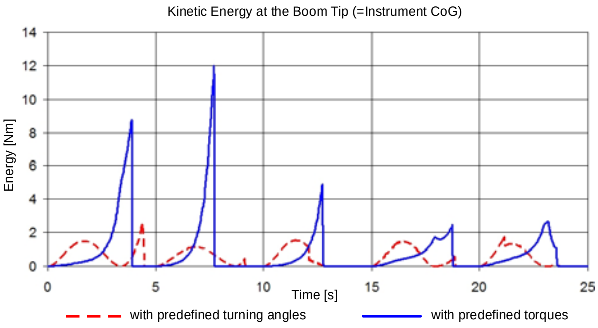

Fig. 13. Kinetic energy for scenario 1

For the uphill movement (scenario 1) it is particularly relevant to consider the relationship between the applied torques and the duration of the driven phase of the turnover movement. The time during which the motor must run so that the CoG can safely cross the apex varies between 3.4 s for the first link, and 3.0 s for the last one.

## 5 CONCLUSIONS

An unfoldable boom for the deployment of scientific instruments with a mass of up to 2.5 kg on planetary surfaces was developed. The boom can carry the instrument horizontally across a distance of 3 m from the lander platform, so that undisturbed access to the planetary soil is secured. It can climb across obstacles such as stones. The boom itself is lightweight, stiff, and can be stowed in a rather small volume during launch and cruise flight. A hybrid drive concept was developed which is largely self-adapting to the local surface contour and brings the boom into a stable final attitude. The control functions are simple and avoid single point failures.

## 6 REFERENCES

1. Ulamec S. et al., The Geophysics and Environmental Package of the ExoMars Mission, *IAC-07-A.3.3.05, 58th International Astronautical Congress*, Hyderabad, India, 2007-09-24 – 2007-09-28

2. Wieczorek M. et al., Landing Site Requirements for the ExoMars Heat Flow and Physical Properties Package (HP3), in: *European Mars Science & Exploration Conference: Mars Express & ExoMars* (Proc.), ESA-ESTEC, Noordwijk (NL), 2007-11-12 - 2007-11-16

3. Figure derived from unpublished project documents, courtesy Martin Pfeil TRAWID GmbH, Hildesheim/Giesen, Germany

4. Sarafin T.P. and Larson W.J. (Eds.)*: Spacecraft Structures and Mechanisms – from Concepts to Launch.* Dordrecht Boston London: Kluwer Academic Publishers; and Torrance (CA): Microcosm Inc., 1995

5. Block J., Structure and Mechanisms, in: Ley W., Wittmann K., Hallmann W. (Eds.): *Handbook of Space Technology*, John Wiley & Sons Ltd., Chichester (UK), 2009, p. 227