DEVELOPMENT OF THE SUPPORT SYSTEM USED ON THE HP^3 INSTRUMENT FOR INSIGHT MARS MISSION

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ABSTRACT

An overview of the development and the qualification process of the Support System is presented. The relevant requirements, the mechanical design and the environmental testing are described.
The mechanical design of the Support System is mainly driven by a new and unique set of requirements derived from the working environment on Mars, the autonomous mechanical operation on the surface and the deployment from the lander deck. The resulting relevant sub-system requirements are presented.
Furthermore the instruments design is explained to show, which design elements have been implemented to ensure proper functionality. One major group of design elements, which is described in detail, are the various mechanisms. Details on the used actuators and their functionality are also presented.
Various verification tests had to be performed in the course of HP^3 Support System development. Besides the standard thermal-vacuum and vibration tests, special tests have been executed to show compliance of the instrument design to the requirements. These tests are: Separation Tests from the lander deck in cold environment and under various tilting angles, Tether Deployment Tests, under various temperatures, foldings and routings, Feet Sliding Resistance Tests, which determine the motion of the instrument in sand under inclined conditions on the Martian surface. The test setups and the results will be shown.

1. INTRODUCTION

The next NASA/JPL Mars mission "InSight" was originally planned to be launched in March 2016. The main objective of the mission is to gain better knowledge of the interior structure and evolution of Mars as an example of a terrestrial planet [1]. The mission has three major instrument packages, a broadband seismometer, a radio science package and a heat flow probe, the "Heat Flow and Physical Properties Package" (HP^3). This instrument consists of several sub-systems, one of which is the "Support System" that will house the mechanical instrument components on the lander deck during flight, during deployment to the Martian surface and on the Martian surface.

The Heat Flow and Physical Properties Packags HP^3 was developed by the German Aerospace Center (DLR) in collaboration with the Polish Space Research Center in Warsaw to measure the surface heat flow of Mars, a geophysical quantity used to constrain the chemistry, the energy balance and the evolution of the planet ([2] and [3]). Although the heat flow is a quantity that is known to vary across a planetary surface according to variations of geologic units, in particular the thickness of the crust, it can be argued [4] that the heat flow measured at the foreseen landing site will be representative of the average surface heat flow.

HP^3 uses a hammering mechanism [5, 6] housed in a cylindrical structure termed "Mole" to penetrate to up to 5m depth. The outer hull of the mole is equipped with heating foils that can be used to locally measure the thermal conductivity of the soil. The mole further pulls the science tether to depth which is equipped with temperature sensors to measure the temperature and the temperature gradient. The heat flow is then the product between the temperature gradient and the thermal conductivity.

In addition to housing the mole and the tether during flight and deployment to the surface, "HP^3 Support System" is required to ensure a stable, nearly perpendicular position of the hammering mechanism relative to the Martian surface before initial penetration. Furthermore, it houses the instruments for length measurement and serves as electrical connection to the lander.

2. THE OVERALL HP^3 CONFIGURATION

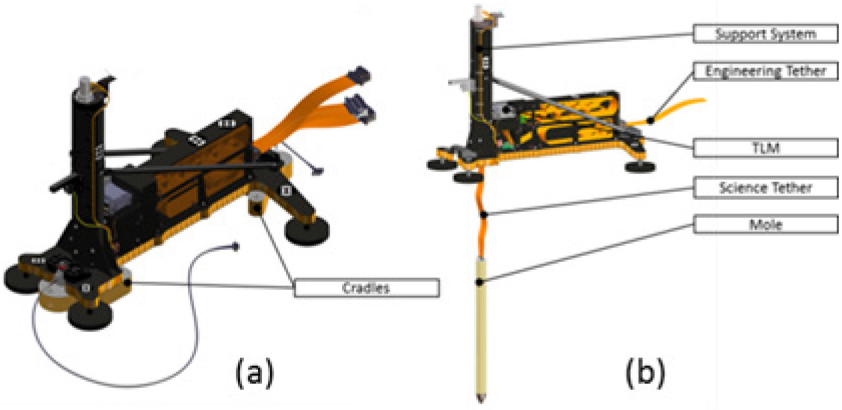

Figure 1: Overview of the HP^3 configuration. Left: Undeployed configuration on the lander deck. Right: Partially deployed configuration

Figure 1 shows the overall configuration of the HP^3 instrument as it would be on the lander deck (a) and the Martian surface (b) operation configuration. The primary element of the HP^3 system is the Mole with the Science Tether. The Tether Length Monitor (TLM) measures the deployed length of the Science Tether to determine together with a tiltmeter inside the Mole the current penetrating depth. Electrical elements such as the Mole, the TLM or other are connected to the Engineering Tether, which represents the electrical connection to the Lander. Instead of being one flat-cable like the Science Tether, the Engineering Tether consists of three separate flat-cables, which are bonded to each other at certain locations. During transfer, the instrument is attached to two Cradles, which are mounted on the lander deck. After separation, the cradles will remain on the lander and the Support System is deployed to the Martian surface.

3. SYSTEM REQUIREMENTS FOR THE HP^3 SUPPORT SYSTEM

From the mission objective and the resulting mission requirements, it can be concluded that the Support System needs to fulfil a new challenging set of system requirements. The following section will give an overview of two high level system requirements, which have major influence on the design. The corresponding sub-system requirements will be explained in the section of each major requirement. Other high level system requirements, which define the operating temperatures or the launch environment, will not be mentioned as these are common for many lander and satellite missions.

System requirement 1: Deployment of the instrument with a robotic arm

The overall mission scenario foresees a robotic arm, which deploys SEIS and HP^3 from the lander deck to the Martian surface. The sub-system requirements derived with respect to the deployment are:

1. The Support System shall have an interface to the robotic arm, which is in one line with the centre of gravity and on the very top of the instrument. Justification: This ensures that the instrument is not in a tilted attitude during deployment from the lander deck to the surface.
2. The interface to the robotic arm shall have a defined free space around itself. Justification: This ensures that the robotic arm cannot damage anything when approaching the instrument, even though it may swing due to the wind on Mars.
3. The separation joints between the Support System and the mounting elements on the lander deck shall be designed to have push-off springs. Justification: These springs shall ensure low separation forces, by separating the Support System from the contact surface on the lander deck cradles.
4. The Support System shall remain on a defined position on the lander deck after actuation of the separation mechanisms. Justification: Different kinds of forces, like wind-force or gravitational forces, act on the separated Support System. Any slippage of the system could negatively influence the deployment behaviour. For example, due to snagging with other elements on the lander deck.
5. The instrument shall withstand a defined pull-force at the interface to the robotic arm. Justification: Due to a malfunction in the overall deployment process it might be the case that the Support System is still attached to the lander deck, but the robotic arm already starts to lift the instrument. Any damage on the interface or of the rest of the instrument shall be ruled out.
6. The instruments position and attitude shall be determined during deployment phase and instrument operation. Justification: It might be necessary to change the anticipated deployment trajectories during deployment to the surface in accordance to the attitude of the Support System.
7. The Support System shall withstand a defined touch-down velocity. Justification: The Support System will touch the surface with a defined velocity. This impact results in additional stresses, which might damage elements of the instrument. For this mission the touch-down velocities are very low, therefore the resulting stresses from the touch-down is negligible in comparison to the stresses resulting by the launch.
8. The Support System shall withstand contact forces, which might occur during deployment as a result of a collision with rigid objects on the lander deck. Justification: This requirement was included to ensure that the Support System, which might swing during deployment, is not damaged due to collision with anything on the lander deck.
9. The extraction of the Engineering Tether from the Support System shall be defined within a certain range. Justification: The minimum pull-out force of the Engineering Tether shall be such that the tether does not spill out of the compartment autonomously. The maximum pull-out force shall not lead to tilting of the Support System during deployment.
10. The maximum mass of all deployed element shall be defined. Justification: This requirement limits the mass of the deployed elements to a defined value, which is driven by the capabilities of the robotic arm

System requirement 2: The Support System needs to be able to function autonomously-mechanically on the Martian surface

After deployment of the Support System, the robotic arm shall be used for different activities. Therefore the Support System must be able to operate on the martin surface without any mechanical support. The requirements were formulated, that the passive design is capable to operate on the Martian surface, even though it may be positioned on a inclined surface or be exposed to dust devils. The sub-system requirements reflect this in various ways:

1. The Support System shall withstand the Martian wind conditions. Justification: It is likely that the instrument will be exposed to dust-devils and other wind conditions, which might lead to a tipping of the Support System. Therefore this requirement ensures that the system is stable also inside a dust-devil.
2. The Support System shall have a defined ground clearance. Justification: The ground clearance ensures, that the only contact points between the Support System and the Martian surface are the feet. Additional contact points due to rocks or similar objects could negatively influence the stability of the system
3. The interior of the Support System shall be protected against dust. Justification: During operation of the instrument, it is very likely that the Support System will be exposed to dust. It shall be avoided, that the dust could enter compartments with sensitive elements such as the compartment for the Tether Length Monitor (TLM). This system is then maybe negatively influenced by the dust.
4. The slippage of an inclined Support System, due to the hammering of the Mole, was defined in accordance to the mission requirements. Justification: The total displacement shall be minimised, as it leads to a tilting of the Mole during early penetration phase.

4. THE SUPPORT SYSTEMS OVERALL CONFIGURATION

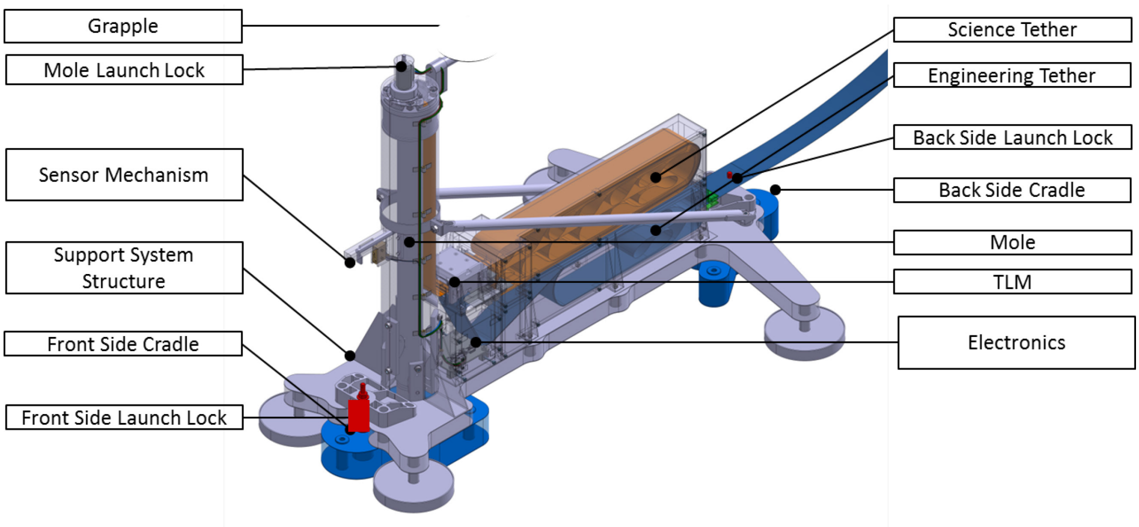

Figure 2 Overview of the sub-systems of the HP^3 Support System

The Support System (incl. Cradles) is a 620x418x453 mm³ large structure. The total mass of all deployed elements is about 3000 g. The overall shape is driven by the available volume on the lander deck and the need to gain wind stability resistance. It can be seen in Figure 2 that due to these two factors the tether storage compartment was designed as long as possible and as low as possible. This gains wind stability, as the wind speed increases with the height. The direction of the feedout of the Engineering Tether was defined by the position of the interface on the lander deck and the overall deployment trajectory. Therefore the position of the Tether and the Mole was defined within the given volume. Unfortunately the available volume on the deck does not allow designing the front feet at a larger distance from the center of gravity (CoG) of the system. Design driver for the position and the number of the feet was the wind stability. Wind stability analysis showed that under the given geometrical boundary conditions on the lander deck, a four feet design has higher margin against tipping than a three feet design.

One of the major design driving elements is the Mole. The Mole is located in a carbon fibre tube at the front of the Support System. The separation mechanism between the Mole and the Support System is at the very top of the tube. A sensor mechanism in the middle of the tube is activated, as soon as the mole passes it. This shall improve the monitoring of the Mole position, as the TLM is only activated after the Mole is buried in the soil. A system of six springs, distributed on two planes along the inner wall of the tube is located at the bottom of the tube. These springs shall ensure on the one hand a defined friction between Mole and Support System, as it needs to be able to leave the Support System, and on the other hand they shall reduce the misalignment of the Mole´s symmetrical longitudinal axis with respect to the tube`s longitudinal axis. As the Mole has a relatively large mass with respect to the other elements, it was deemed necessary to fix the Mole at its tip during launch, transfer and landing. During transfer to Mars the tip of the Mole is held in a cone, which is attached to an aluminum insert inside the front side Cradle. The distance between the cone and the tip of the Mole can be adjusted with a thread to be able to handle manufacturing tolerances.

The tethers are another design driver for the Support System. They are located in the Tether Storage Compartment, which is a removable carbon fibre box. This box is separated into two compartments. Each compartment has a size of approx. 300x60x37 mm^3 into which the tethers need to be folded. During the project, different folding strategies were investigated. One of the major concerns was the possibility of an uncontrolled unfolding during deployment. The chosen folding strategy is called "recumbent loop folding". This folding leads to a small number of bends with comparably large bending radii. During the complete deployment phase, the tether has friction contact to itself generating a constant pull-out resistance.

The Engineering Tether is located in the bottom compartment. A Tether Retaining System is installed at the feedout towards the lander. This Tether Retaining System limits the pull-out force to a defined value and also prevents the tether from spilling out uncontrolled from the box. There is also another slit on the opposite side of the Tether Compartment where the three flat-cables of the Engineering Tether are divided. The bottom cable, which has a connector PCB at its end, remains in front of the box and is attached to the structure. Electrical elements such as the heater and separation mechanisms are connected to this board. The other two flat-cables of the tether are directly connected to the Science Tether in the upper compartment.

The Science Tether is folded in the same manner as the Engineering Tether into the upper compartment of the Tether Storage Compartment. Similar to the Engineering Tether compartment, a slit is used to feedout the Science Tether through the TLM until it reaches the tube with the Mole. It is then carried upwards parallel to the central axis of the tube until it ends at the backcap of the Mole, where it is rigidly connected. This routing of the Science Tether leads to the disadvantage of the lack of ability to measure the position of the mole at initial penetration. But other options, at which the Science Tether had an additional guidance at the top of the tube, resulted in undesirably high friction forces between the temperature elements of the Science Tether and the structure.

As the TLM is an optical instrument to determine the deployed Science Tether length, it is located in front of the slit of the Science Tether Compartment in a separated dust-protected compartment. Two rows of brushes at the inlet and outlet of the compartment were included to reduce the dust contamination of the inner volume. These brushes only apply a small friction force on the tether, but at the same time provide a good resistance against dust and are very small due to space limitations. Additional brushes are installed on the TLM. But the design has been improved to provide much less stiffness and higher reliability against small bending radii. Also these brushes are wider than the tether in order to seal the whole slit.

5. DESIGN DESCRIPTION OF THE SEPARATION MECHANISMS

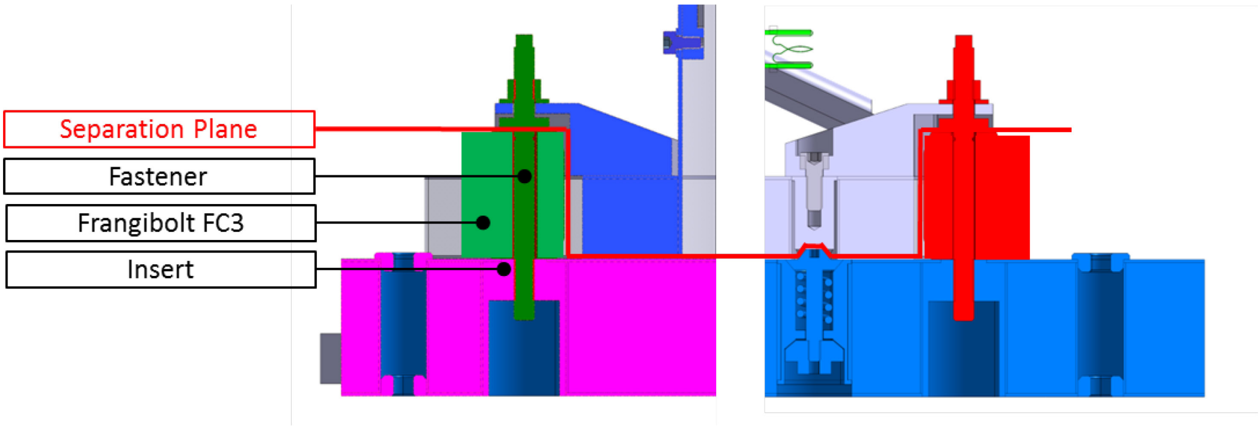

Figure 3 Overview of the separation mechanism between the Cradle and the Support System

The Support System needs to have mechanisms which separate the Support System from the Cradles and separate the Mole from the Support System. The main actuators of the mechanisms are Frangibolts manufactured by TiNi Aerospace [7].
The separation mechanism between the Support System and the Cradles (see Figure 3) consists of two separately acting mechanisms: One at the front side and one at the backside. Both mechanisms have the same configuration: A customized #10 titanium bolt is fed through the Frangibolt and mounted to the Cradle. Afterwards the bolt is torqued to have a defined preload. At the second step the Support System is placed onto the Cradle. Due to tolerances it is very likely that there will be a small gap between the mounting flanges of the Support System and the fastener. Therefore washers are added between Support System and fastener to reduce the gap to a defined size. At the last assembly step the nuts are added to the top of the fastener and the Support System will be preloaded against the Cradles. The load transmission into the structure of the Support System is done by aluminum mounting flanges. Both Cradles also have Push-off Springs to lift the Support System approx. 0.8 mm after breaking the Frangibolt bolts. The Push-off Springs consist of a conical pin and a spring, which are assembled inside an insert. This insert is glued into the Cradle. After separation the position of the Support System is defined by these Push-off Springs. The cup-cone configuration at the front side Push-Off Spring avoids radial motion of the Support System after release. The Back Side Push-Off Spring has only a lateral form-locked connection with the Support System to avoid a mechanically over-constrain bearing, which might lead to problems due to thermal expansion.

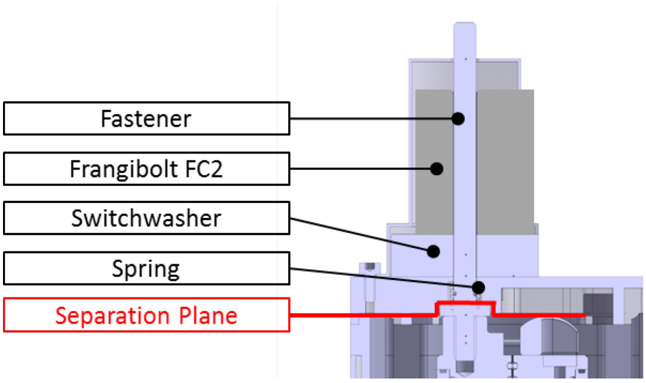

Figure 4 Overview of the Mole to Support System separation mechanism

The Mole is connected to the top of the Support System by a #8 bolt. Between the head of the bolt and the Mole there is a FC2 Frangibolt, a Switchwasher, and a Push-Off Spring. (see Figure 4) The Frangibolt actuator is used to fracture the fastener. The Switchwasher is used to detect the successful fracturing of the fastener. After the bolt has been fractured, the Push-Off Spring pushes the mole 1-2 mm along the central tube axis.

6. VERIFICATION OF THE MAJOR SYSTEM REQUIREMENTS

The overall HP^3 instrument qualification was done in accordance to a protoflight strategy. This resulted in a demanding qualification campaign of the flight-unit. The system was qualified using thermal-vacuum, mechanical-dynamic and system deployment tests. Beside the deployment tests these tests can be seen as standard for every space instrument. Therefore they will not be further explained. The majority of the sub-system requirements were verified by tests. Therefore the Support System to Cradle Separation Tests, the Engineering Tether Pull-out Tests, the Feet Sliding Resistance Tests and the Rocking Tests are presented here. Two models of the Support System were used for the different tests as test object. Firstly, relevant sub-assemblies or the full flight representative prototype model for separation and engineering tether pull-out test. Secondly, a mass model for sliding and rocking tests. The mass model has a similar configuration as the flight-unit at the relevant points, but was designed to have the same resulting gravity force on earth as the flight-unit on mars.

<u>Description of the Engineering Tether Pull-out Tests</u>

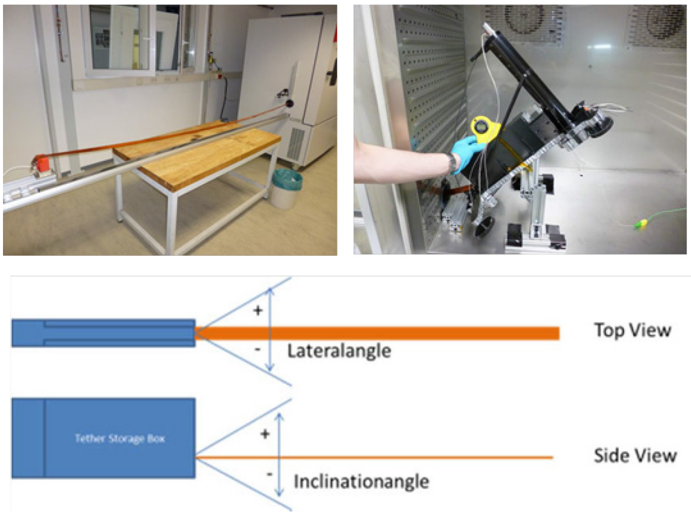

Figure 5 Overview of the Test setup for the Engineering Tether Pull-out test and the pull-out angles

Scope of the Engineering Tether Pull-out Tests was the determination of the extraction force of the Engineering Tether with the flight-like Tether Retaining System at different temperatures and different pull-out angles. The temperature range varied between -60°C and +20°C. The pull-out angels were separated in lateral pull-out angles and longitudinal pull-out angles. The lateral pull-out angles were tested up to 25 deg, the longitudinal pull-out angles were tested up to 45 deg. (see Figure 5 bottom) This test campaign was used to verify, that the pull-force is within the requirement specified limits. The tests were performed at the climate chamber of DLR Bremen and the center of applied space technology and microgravity (ZARM) [8]. The test setup varied in some parts from test to test. Therefore only the key elements of the test setup will be described. For some pull-out tests, the whole Support System was used, but as it is more variable and at the same time still flight-like, it was deemed acceptable to just use the Tether Storage Compartment for the majority of the pull-out tests. The Support System (or just the Tether Storage Compartment) was placed in a tilted configuration inside a climate chamber. (see Figure 5 top right) Afterwards the end of the Engineering Tether was led through a feedthrough out of the chamber and connected to the three-axis force gauge on a linear unit, which is located in one line with the axis of the feedout of the chamber. The length of the linear unit was chosen to be sufficient to deploy the Engineering Tether completely with constant speed. The pull-out process outside the chamber was also monitored by a camera placed on the outside wall of the climate chamber. The inner volume of the climate chamber was flushed with dried, filtered air to avoid ice on the structure, which would influence the deployment forces. After the climate chamber was flushed with dry air, it is set to the given temperatures. Thermal elements were installed in the engineering tether compartment to monitor the temperature during test. The linear drive was activated as soon as the force gauge started measuring. The analysis of the test data showed, that the influence of the vertical pull-out angle is negligible for the chosen design of Tether Retaining System. As expected, the lateral pull-out angle influences the pull-out forces significantly. But even though the lateral pull-out angles influenced the pull-out force, the test showed that forces are within the given range of the requirement.

Description of the Support System to Cradle Separation Tests

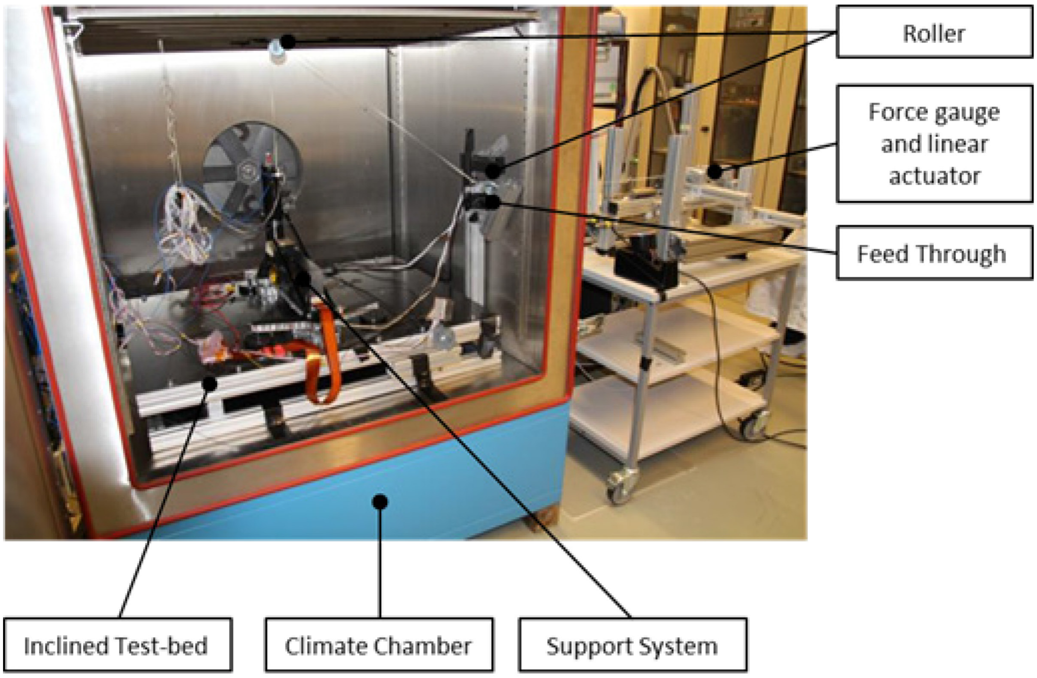

Figure 6 Overview of the test setup for the Cradle to Support System Separation Test

The Support System to Cradle Separation Test was used to determine the lifting force and the positional stability of the Support System after separation at various temperatures. The shocks induced by the Frangibolts during separation were also determined with this test. The determination of all these parameters was performed to verify the successful separation of the Support System and Cradle. This test was also performed inside a climate chamber. Beside the temperatures, also the tilting angle of the instrument was varied during test campaign. This is done due to the possibility of a slightly tilted lander deck during operation. Therefore the Support System was tilted +/-15° horizontally in both directions. Figure 6 shows the test setup for this test, which was designed to be able to lift the Support System inside the climate chamber at the full range of temperatures. Therefore two rollers were installed inside the chamber: One roller at the top and one roller at the feedthrough to the outside. A linear actuator with a force gauge was installed outside in front of the feedthrough. A rope was attached to the force gauge, guided through the first and top roller and attached to the Support System, which is installed on a tilting device at the bottom of the chamber. The Support System itself was monitored by accelerometers to determine the shock from the Frangibolts and by a camera, which recorded the motion after separation and during lifting. The test was performed in nine different combinations of inclination and temperature of the Support System. Three tests on the un-inclined testbed at -40°C, +20°C +40°C and six tests on the 15° inclined testbed with 3 different orientations relative to the slope also for -40°C and +40°C. In order to avoid overtesting of the structure and to reduce the number of fractured bolts, the fracturing of the bolts

was only done for the test runs in cold and ambient temperature. Before starting the test in cold conditions the climate chamber was flushed with dry air. Afterwards, the two Frangibolts were activated separately. During activation of the Frangibolts, the internal temperatures, the current draw, and the activation time were measured. The Support System was lifted about 100 mm shortly after the bolts fracture. At the end of the test sequence the Support System was lowered again on the Cradles. One of the major outcomes of the test was a successful demonstration of the separation. Nevertheless it was also observed that at one test configuration the front foot of the Support System clashed with the un-covered honeycomb of the Cradle, which leaded to approximately 50% higher lifting forces. For the flight-model the honeycomb is covered with Kapton to avoid high peak forces during lifting. An additional outcome of these tests is the determination of the shock loads from the separation. Comparing the shock curves to the shock loads provided by the InSight mission, it can be stated that the loads from separation are much higher than the launch and descent shock loads. As a result the shock loads of the qualification campaign of the instrument were modified to a combination of Frangibolt shocks and launcher shocks.
The Engineering Tether Pull-out Test and the Support System to Cradle Separation Test were both closely related to the deployment of the instrument. In order to verify the on-surface behavior of the instrument the Feet Sliding Resistance Test and the Rocking Test were performed.

Description of the Feet Sliding Resistance Tests

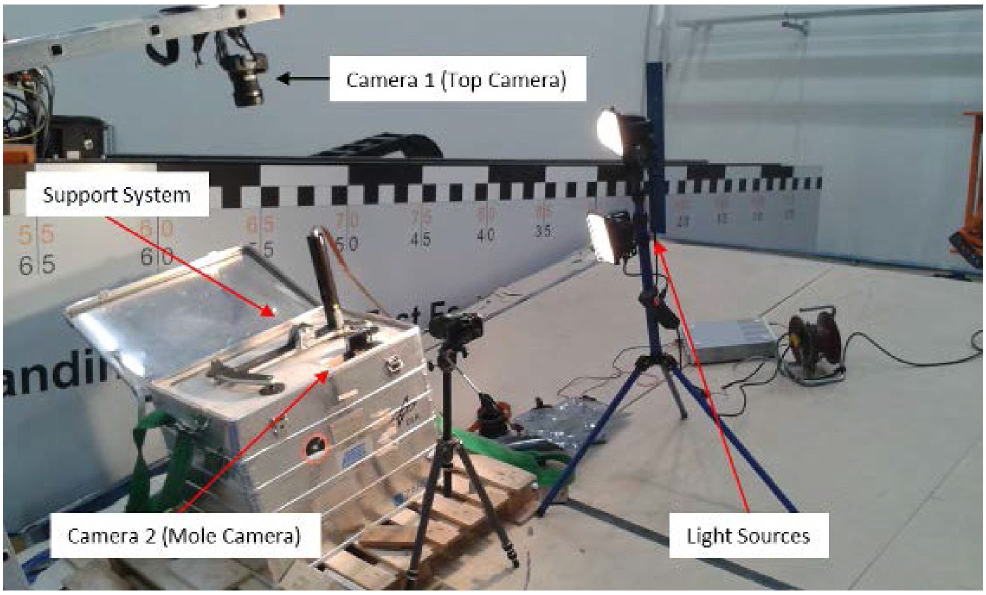

Figure 7 Overview of the test setup for the Feet Sliding Resistance test

The Feet Sliding Resistance Test was performed to determine the relative displacement between the Support System and a 15° tilted surface during initial penetration of the Mole. Besides the verification of the acceptable instrument motion this test also verified a successful exiting of the Mole from the Support System. This test was performed in two Support System configurations. The first configuration was the Mars representative Support System model. For the second configuration masses were added to the mass dummy, such that it has same CoG and mass as the flight-unit under earth gravity. All in all six test configurations were performed to test three Support System attitudes relative to the inclined slope with mass configuration for Earth and Mars. The test was performed in the Landing & Mobility Test Facility (LAMA) of the DLR Institute of Space Systems. The overview of the test setup can be found in Figure 7. A box was filled with WF34 quartz sand to simulate Martian surface. The surface of the soil has been flattened. The whole box was inclined by 15° and the Support System and Mole were put on the testbed. Two cameras were used to record the whole test. Before starting the test the position of the Support System was determined. Afterwards the Mole was activated and switched off as soon as it reached the minimum depth of approx. 500 mm. At the end of the test the position of the Support System was determined again. In addition, video tracking software was used to determine the motion of the Support System between start and end of the Mole penetration. The test results showed that the relative displacement is below the required threshold. Furthermore it could be observed that the motion of the instrument is much larger for Mars configuration than for Earth configuration.

Description of the Rocking Test

After the deployment of the Support System on the Martian surface, it may happen that the Support System is in an unstable configuration due to rocks under one or more feet. The Rocking test assumed a worst case scenario, at which there is one rock underneath the +Y front foot and one rock underneath the –Y back foot. In addition there are depressions of 1.5 cm underneath the other feet. The rotation of the Support System around the axis which connects in the worst case scenario the two rocks will be referred as rocking. Rocking can occur due to various reasons during two phases of the initial penetration:

1. Mole starts hammering and is still inside the Support System, but penetration depth is not deep enough that the Mole can act as an anchor. This could lead to a tilted mole penetration. As the mole is able to penetrate from a variety of angles, this can be considered acceptable.
2. Mole has left the Support System. A rocking of the Support System could lead to a snagging of the Science Tether (ST) within the Support System. The Rocking Test verified that the Science Tether does not snag inside the Support System, after the Mole has left

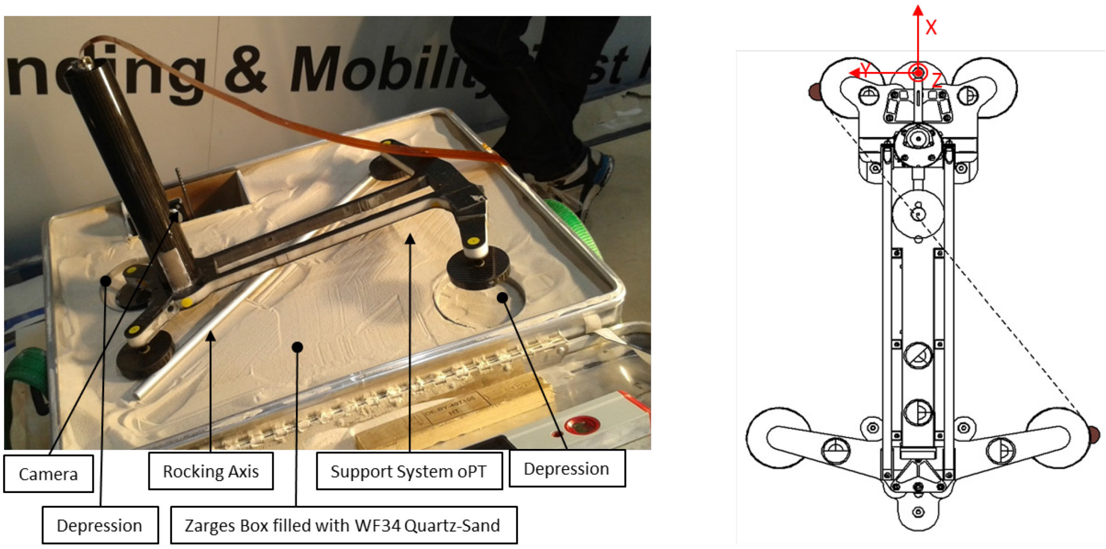

Figure 8 Left: Overview of the test setup of the Rocking Test. Right: Schematic topview with rocking axis and coordinate system

The Mars representative model of the Support System was used as the test object. The same test setup as for the Feet Sliding Resistance Test was used, except for the modification of the sand bed, which can be seen in Figure 8. The box was filled with WF34 quartz sand and was inclined by 15° as for the Feet Sliding Resistance test. A bar with a diameter of 15 mm was used to simulate the two rocks. The longitudinal axis of the bar is in one line with the assumed rocking axis. The bar starts at the +Y front foot and ends at the –Y back foot. The distance between the horizontal surface of the sand and the upper edge of the bar is 1.5 cm. Two tubes with a diameter of 125 mm were used to ensure circular depressions below the –Y front foot and the +Y back foot. The Support Structure was positioned on the sand in the box. Different cameras were used to monitor the Support System motion.

The test was started with the –Y front foot in the depression. After the Mole has left the Support System, it was tilted around the rocking axis such that the +Y back foot is in the depression. In the initial phase of Mole penetration the Support System starts significantly moving towards the tilting angle of the box. This is mainly caused by the Mole shocks in combination with a low friction contact between the sand and +Y front foot. The motion stops as soon as the –Y front foot is partly covered by soil and the +Y front foot has contact with the soil (see Figure 5 for details). Although the Support System was moving, the +Y front foot still remained on top of the rocking axis.
Besides the sliding of the Support System the penetration behaves nominally. No snagging of the Science Tether in the Support System was observed. After the Support System was tilted the Science Tether was slightly twisted, but the penetration behaved nominally. Additionally the Science Tether was inspected afterwards to rule out any damage coming from the Support System. The inspection did not show any anomalies on the Science Tether.

8. CONCLUSION AND OUTLOOK

An overview of the development process of the HP³ Support System was shown in this work. The requirements derived from the deployment and the autonomously-mechanically operation on the Martian surface were presented. Furthermore there implementation into a lightweight design, as well as excerpts of the verification program were described. This verification program included new verification and development tests, which were also addressed here.
Comparing the mission scenario of the SEIS and HP³ instruments, it is very likely to find different solutions of similar technical challenges. This might be the result of a lack of a general applicable verification strategy for these instruments. Therefore the introduction of a definition of these instruments shall be further studied and it shall be investigated to find a generalized overall verification process, which is applicable for this class of instruments. This shall reduce the development effort significantly in the future.

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