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ESA ESTEC
Noordwijk, The Netherlands

Bionics and
Space System Design

A Deployable Digging Mechanism for Sampling below Planetary Surfaces

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D'APPOLONIA

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A Deployable Digging Mechanism for Sampling below Planetary Surfaces

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1 BACKGROUND

Biomimicry is a multi-disciplinary science involving a wide diversity of other domains like electronics, informatics, medicine, biology, chemistry, physics, mathematics, and many others. However, it is quite unusual to find key people or expertise centres that have cognition and expertise in all these disciplines as a whole. Therefore, there is a need for the establishment of a capillary network of contacts through Europe and elsewhere that will enable to reach also those academic centres, which are not much visible due to their reduced dimension or recent origin. Additionally, although some peculiar conditions characterizing space environments can be similarly encountered on earth (e.g. desert zones) and specific solutions found within these terrestrial contexts can be adapted to space conditions, there is a majority of cases, which are subject to conditions which are broadly different from those encountered on earth (e.g. gravity absence). Therefore, the biomimetic approach in the space sector results more complex and has to be considered in a multidisciplinary and cross-sectorial framework to overcome barriers. The problems to be addressed to exploit the potential of the biomimicry approach in the space domain can be summarized as follows:

- biomimicry has become a real science only in recent years and therefore there is no consolidated co-operation environment with space engineers;
- research in biomimicry across Europe and Canada and more generally at world wide level is scattered and fragmented, it is not easy to locate the proper academic experts for a given space application;
- biomimicry is a multi-disciplinary science and it requires several expertise which is difficult to locate in the same organization;

- some databases with information about possible natural phenomena, biomimetic products, ongoing biomimetic research, biomimetic researchers, published articles exist, but they lack a systematic and a large-scale exploration of the potential of nature in view of applications in engineering, especially as far as the space domain is concerned;
- in current knowledge-basis the abstraction of the biological functionality is missing, therefore solutions inspired by nature are sporadic and random-governed;
- space conditions are completely different from life forms habitats and space engineers are so far not fully aware of applications of biomimetics.

Therefore, the overall objectives of the study consists in the development of a co-operation platform between space and biomimicry experts in order to bridge current gaps that exist for an effective application of natural mechanisms and phenomena in space system design and to foster the development of a new generation of space systems. This has been achieved by:

- performing a comprehensive collection and review of information concerning attempts made since today in Europe and elsewhere in finding solutions through a biomimic approach, including an insight into planned research activities and trends;
- developing a detailed biomimicry knowledge map that allows to identify expertise and competencies in ESA member states and elsewhere;
- providing an overview of the unique characteristics and properties of various life forms found in nature (e.g. animals, plants, etc) and to ascertain whether these characteristics could be an inspiration to create innovative space systems;
- conceptualising several innovative space systems and components which incorporate the design, features and mechanisms of nature's life forms.

All the gathered information have been implemented into a database which is available online at www.bionics2space.org. The added value of the database is in the deep analysis made on each biological system described, supported by literature and reference articles, patents, etc.

The project group has then been focusing on the analysis of the information collected and on whether any of these biological principles might hold potential for application to the design of space systems or provide solutions to space-related technical challenges.

Therefore, the project group has identified twelve different cases in which the application of biological principles could bring a real added value to the solution of technical constraints within the space field. The identified case studies are reported below:

- deployable digging mechanism for sampling below planetary surfaces;
- energy storage structures for deployable systems;
- rigidisation of deployable structures;
- smart swarm on mars;
- robust biologically inspired navigation techniques;
- planetary exploration with free energy (based on sun flowers);
- adaptive and versatile biologically inspired locomotion control;
- balance between adaptability and stability;
- automatic self-assembly in space;
- landing and planetary exploration;
- energy storage structures for deployable systems;
- planetary exploration with free energy (based on dandelion seeds).

Such work has set the base from which a more detailed analysis has been performed: for each of the topics, a responsible among the Bionics Expert Team has been identified; such expert has been in charge of providing to the partners the assessment of the idea of application.

The results of such detailed analysis have been presented in the framework of the Bionics workshop held in ESTEC on November 2004. The output of such event has been the selection of four case studies which have been further assessed by proposing first attempts of engineering solutions inspired by nature. Such case studies are the following:

- energy storage structures for deployable systems;
- case study on adaptability versus stability;
- deployable digging mechanism for sampling below planetary surfaces;
- landing and planetary exploration.

In this report the work undertaken for the “deployable digging mechanism for sampling below planetary surfaces” is described.

2 A DEPLOYABLE DIGGING MECHANISM FOR SAMPLING BELOW PLANETARY SURFACES

2.1 INTRODUCTION

The search for possible extinct or existing life is the goal of the exobiology investigations to be undertaken during future Mars missions. As it has been learnt from the NASA Viking, Pathfinder and Mars Exploration Rover mission, sampling of surface soil and rocks can gain only limited scientific information. In fact, possible organic signatures tend to be erased by surface processes (weathering, oxidation and exposure to UV radiation from the Sun). The challenge of the missions have mostly been getting there; only roughly one third of all Mars missions have reached their goal, either an orbit around the planet, or landing to the surface. The two Viking landers in the 1970's were the first to touch down the soil of Mars in working order and performing scientific studies there. After that there was a long gap, until 1997 the Pathfinder landed safely on the surface and released a little rover, the Sojourner. In 2004 other rovers came: the Mars Exploration Rover Spirit and a while after that, the sister rover Opportunity. These five successful landings are less than half of all attempts to land on Mars. Russia, Europe and the United States have all had their landers, but Mars is challenging. Even Mars orbit has been tough to reach by many nations' orbiters. It is then understandable that of these five successful landings, performed by National Aeronautics and Space Administration (NASA), there have not yet been very complicated mechanical deep-drilling instruments onboard. The risks to get there are great, and the risk of malfunctioning of a complicated instrument there is also high. Another reason to avoid a deep-driller from the lander payload is simply the mass constrains. A drill is a heavy piece of payload, and the mass allocations for scientific instruments are small. In the launch window of 2009, both European Space Agency (ESA) and NASA have their plans to send a rover to Mars. Both of them will include some means to analyse the subsurface material. ESA's rover, called the ExoMars rover, will carry a deep-driller onboard in its Pasteur payload.

Any machine sent into space has to justify its payload: a digging mechanism has to be light as well as effective. Since weight and strength usually go together, a lightweight drill will either have all the force concentrated in a small area – where the digging is actually being done – or transmit the force in tension, which avoids stability problems in long structures such as drills that are reaching down into the substrate. By comparison an oil drill transgresses both these design rules. The engine is at the far end of the drill from the cutting edge, out in the open air, and the force is transmitted to the cutting edge by a combination of compression and torsion (shear) along the tubes of the drill. This means that the tubes have to perform two functions – force transmission and tubular guidance – when they need perform only the tube function and thus be much lighter.

The particular type of digging mechanism that will be examined here is the one where the machinery is entirely concentrated at the 'work face' of the hole, and it can be defined as a terminal drill.

2.2 SPACE REQUIREMENTS AND STATE OF THE ART

Mars has an atmosphere, but it is quite different from that of Earth. The main constituent is carbon dioxide, with only small amounts of other gases, such as nitrogen, argon and oxygen. The Martian atmosphere contains only about one thousandth as much water vapour as the Earth's atmosphere, still this amount of water can condense out, forming clouds high in the Martian atmosphere. Even some local patches of early morning fog can form in deep valleys. At the Viking Lander 2 site at Utopia Planitia (Zubrin, 1996), a thin layer of water frost (NASA, 2004a) covered the ground each winter during the mission's lifetime in 1976-1980. This frost period lasted for a third of the Martian year. The atmosphere is so thin, that it cannot support liquid water on the planet's surface. There is still some evidence that in the past Mars may have had a denser atmosphere. For millions of years ago, there may have been flowing water on the surface. Orbiters have imaged physical features, which seem to be shorelines, riverbeds and islands. These features suggest that great rivers once existed in Mars. But the surface pressure is not the only factor that affects to the existence of liquid water: the average (recorded) temperature on the Red Planet is -63°C with a maximum temperature of about 25°C and a minimum recorded temperature of -140°C (Williams, 1999). The average atmospheric pressure on the surface is only about 7 millibars, but it varies greatly with altitude from about 10 millibars in the deepest basins to only 1 millibar at the top of the Olympus Mons mountain. Despite that the Mars' surface pressure is very low (Mars' surface pressure is equal to Earth's atmospheric pressure at 30 km height), the atmosphere is thick enough to support very strong winds and vast dust storms. These storms occasionally engulf the entire planet for several months. Mars' thin atmosphere produces a greenhouse effect but it is only enough to raise the surface temperature by 5°C; much less than can be seen on Venus or Earth. Another issue affecting Mars' surface temperature is its orbit. Unlike Earth's orbit, Mars' orbit is highly elliptical. Between aphelion and perihelion (orbit's farthest and closest point to the Sun, respectively), the average temperature variations are about 30°C. So the orbital phase, together with the tilted rotation axis, has effect to Mars' climate. The temperature and the atmospheric pressure are both factors that must be taken into account when designing a drilling and sampling machine into Martian environment. Basically, the pressure issue is similar to when dealing with vacuum conditions, although even the thin atmosphere of Mars has some effects regarding the dust accumulation and thermal issues, in some means also to the electric charge exchange (NASA, 2004b). The atmosphere in Mars, despite being only about 1/150 of Earth's atmospheric pressure, is actually a good matter for thermal issues. In pure vacuum conditions the variations of shadow and light are extremely sharp, and the temperature variations are extreme and fast. This exposes the structures to larger thermal stress, possibly causing mechanical damage in shorter time than in a situation where thermal differences occur in longer time interval.

The optimum strategy for taking samples depends on many factors, but mostly it depends on the required size and nature (or form) of the target object. In this study, the emphasis has been given to sampling soil samples from surface or within a few metres depth from the surface. One factor that affects greatly to the sampling operation is the environment and target celestial bogy. These factors can be divided into:

- gravity;

- the material form of the sampling location (e.g. solid rock, hard soil, porous/spongy soil, liquid etc.);
- possible atmosphere;
- temperature;
- solar radiation.

The gravity and the local terrain type are the most dominant factors. However, in extreme conditions, like on the surface of Venus, the temperature is one the most critical factors. The gravity, or rather the lack of gravity, is a challenging factor. This issue was faced when the SD2 drill was developed to the Philae lander of ESA’s Rosetta mission (DLR, 2004). Philae is going to land on a comet Churyumov- Gerasimenko in 2014 and perform drilling and sampling there. However, since the comet has virtually no gravity at all, the lander must attach itself to the comet by harpoons. Philae’s drill needs counterforce to sustain the drilling operation. The main focus of this study is to conceive a digging device in Martian conditions, where there is significant gravity (0.37 m/s2 ˜ 0.38 g). While there are several possible sampling methods proposed for different kinds of missions to planets, comets and asteroids, the methods that are potential options at the Martian surface are:

- Claw, scoop or trowel;
- Tongs/pincers;
- Drag lines and nets (throwable net etc.);
- Drillers (deep drillers and surface drills) and corers;
- Penetrators;
- Drive tubes and penetrators;
- Passive/adhesive surfaces;
- Brush sweeper;
- Gas jets.

In addition to these sampling methods, there are several ways to actually reach the sampling location. For example, the Viking lander was a stationary lander, and it took samples from its surroundings by scooping. The scoop was attached to a boom, i.e. robotic arm. All these methods have their benefits and drawbacks. Some of them are suitable only for surface sampling, and some are possible methods to access subsurface material and retrieve it for analysis. Also the sample handling includes several kinds of tools, ranging from brushing to percussion tools.

Figure 1 shows six possible sampling methods. Method a), the scoop, has been used during the Viking 1 and 2 missions to Mars in 1976-1982 and during the Venera missions to Venus in 1980's. The Viking lander's sampling arm created a number of deep trenches as part of the surface composition and biology experiments on Mars. The digging tool on the sampling arm (at lower center) could scoop up samples of material and deposit them into the appropriate experiment. Some holes were dug deeper to study soil which was not affected by solar radiation and weathering. Tongs/pincer (MEE) shown in Figure 1b were developed for the SSA/DT project. The Surveyor Lunar lander carried a "lazy-tongs" mechanism to dig lunar soil. The tongs' end-effectors were quite different to those in the Figure 1b, and the scoop was attached in an end of a robot arm. Drag-line buckets or nets (Figure 1c) have been proposed for example for a sampling mission to Moon (Ylikorpi, 1994), although none of them have been flown or assigned to future missions yet. Method 1d, the drill, has been used so far in Luna, Apollo, Venera and in ongoing Rosetta mission. Image shows the Luna 16&20 drill. Rosetta's SD2 drills more than 20 cm into the surface, collects samples and delivers them to different ovens or for microscope inspection. The first drill that has operated in another celestial body than Earth was the Russian Luna 16 drill. The drill was attached to a robotic lander that returned its sample back to Earth. Following that, there were the Apollo 15-17 missions, where astronauts used hand drill (the Apollo Lunar Surface Drill, ALSD) to retrieve subsoil samples. In addition to lunar missions (three Luna landers and Apollo 15-17 missions), the Russian Venera landers had a robotic driller too. The trend, if the term may be used, is towards miniature drillers. Terrestrial drilling could relay on virtually limitless power, thrust and torque. Unfortunately this is not case with planetary exploration drilling.

During the Apollo missions, the astronauts used the ALSD to retrieve core samples down to three metres depth. The drill was not very big, but the "mechanics module" for attaching and detaching the drill strings was the astronaut himself. The dexterity of astronaut in surprising situations is unbeatable, e.g. when the drill gets stuck. However, it is not possible always to send astronauts instead of robots. The challenge is to get a robot to use a miniature drill in all possible drilling-related situations.

Besides of several small drill devices, such as the Luna, the ALSD or the Venera drills, there have been plans to develop huge drills, which would be capable to reach tens of metres depth, even kilometres. NASA had plans in 1960's to equip post-Apollo manned missions with a colossal coildrilling device. As known, there were no post-Apollo manned Moon missions, so the coiled drill was never flown. There was also not any technical reference for the drill system, so it remains unknown whether this kind of coiled drill could be scaled down for robotic missions. NASA has also some newer plans for coiled drill strings.

A penetrometer (Figure 1e) is basically a stick that is pushed down to the soil. The soil properties can be analyzed by several methods by using a penetrator, and different instruments in penetrators may reveal for example temperature, moisture, adhesion and electric properties. There are several different kinds of penetrometers, and one classification can be made by the penetrating method; impact or active and slow pushing force. A mole is like a penetrometer, but it is (usually) connected to the lander (or other platform) by a tether instead of rigid structure as penetrometer is. The Beagle-2 mission to Mars had a mole, but unfortunately the landing was unsuccessful.

There have been several penetrometer instruments onboard planetary landers. One of the first was the penetrometer used in Lunokhod Moon rovers. In addition to penetrometer instruments, there have been plans and attempts to use penetrating spacecrafts, which lands like a dart to target body (comet, planet surface etc.). These surface penetrators have been designed to survive an impact of possibly tens or hundreds of g's, measuring and telemetering the properties of the penetrated surface back to orbiting spacecraft or directly to Earth. So far no penetrator spacecraft have been successfully operated. An example of a penetrator spacecraft is the twin Deep Space 2 penetrators, which piggybacked to Mars aboard the Mars Polar Lander and were to hit into Martian soil on December 3, 1999. The faith of these two penetrator spacecrafts is unknown, since they were never heard from. Drive tubes (Figure 1f) are generally used to extract a soil sample for density analysis or for extracting whole core sample from adhesive soil. Three models of drive tubes were used in Apollo flights. Early tubes were sometimes hard to drive into the compact lunar regolith and did not always retain the core when removed. By the time Apollo 15, a new, thin-walled, larger diameter core tubes were designed and worked well. During Apollo 16, it took 5 minutes to get a single core tube and 11 minutes for a double core tube. Robotic spacecrafts have used drive tube designs in their drill sampling tool heads. The drill bit contains a sample container, which extracts the core sample from the bottom of the borehole. There have been some studies to drive tubes for cometary (Amundsen, 1987), Mars surface and lunar sampling, down to a depth of about 10 cm. Required power would be between 0.5 and 1 W and sampling efficiency ranging from 1.2 to 6.6 J per sample (1.9 cm3 sample). This kind of drive tube is shown in Figure 2.

2.3 BIOLOGICAL PRINCIPLE

Most animals have a front end and a back end. There are two main types of terminal drill: those where the substrate is passed inside a tube behind the digging mechanism (typical of a front-end digger), and those where the substrate is thrust aside to allow a tube or column to pass through without having to take material into its lumen (a back end digger). Either end can dig, and it’s more common that the front end digs since the spoil removed from the substrate commonly contains food items. Thus many worms which make burrows do so by ingesting the substrate in from of them, using rasping teeth or roughened surfaces, digest the organic matter, and eject the material from the back end when they return to the surface. This raises the possibility of a novel type of sampling system that has constant through flow. The drill at the front end (however actuated – see below) delivers the spoil into a continuous system that subjects it to various chemical transformations and measurements, and finally ejects the degraded sample from the other end. Such a sampling and analysing machine would use the acquisition of samples as the main part of its locomotion system as well, since it can burrow with no net displacement of the substrate. Since there would also probably be a surfeit of material going along the sampling/analytical canal, the data could be treated statistically.

Specific examples of ‘worms’ (actually bivalve molluscs) are Teredo (which bores into wood and is an important pest of wooden ships, piers, piles, etc), (Figure 3) and Pholas (which bores into rock), (Figure 4). The two half-shells are modified to act as a reciprocating drill. In Teredo they form a sort of shield at the front, which became the inspiration for Marc Brunel’s design for the excavating machinery used in the Blackwall Tunnel under the River Thames. In neither case is the precise mechanism of the drill understood. Where, for instance, does the reaction force come from to fracture the wood ahead of the Teredo? With Pholas this is a little more certain since it produces dilute HCl which dissolves any carbonates in the rock.

A mechanism which has been investigated is the digging ovipositor ‘valves’ of the female locust (several species, though the one which has been investigated is Locusta migratoria).

When females of locust species such as Locusta Migratoria, Schistocerca gregaria (Forskal), S.peregrina (Olivier), Anacridium aegyptium and a number of other Acrididae (Snodgrass, 1935; Jerath, 1968) dig oviposition holes they stretch the intersegmental membranes between abdominal segments IV, V, VI and VII and thus make a hole considerably deeper than could otherwise be achieved.

Snodgrass (1935) was the first to state that it is the ovipositor valves which provide the force for this extension, a suggestion since supported by Vincent & Wood (1972) who showed that the haemolymph is not under pressure while the hole is being dug, so that the insect cannot be pumping itself up in order to elongate.

That the ovipositor valves can provide the motive force was pointed out by Rainey (1973). What is much less clear is how they work to dig a hole and pull the abdomen down. Snodgrass (1935) says that the ovipositor “is a boring machine which, once set in motion with its prongs against the soil, must automatically bury itself and in doing so it will stretch the easily extended abdomen to its full length, so long as the insect maintains it hold on the ground.

Figure 5 shows the movements of the ovipositor valves and terminal abdominal segments during a complete cycle of digging. For ease of illustration the abdomen tip is shown moving from right to left; the natural position is obtained by rotating the figure 90° anticlockwise. The frames have been drawn is such a way as to stimulate the postulated displacement during digging (the actual preparation could not move bodily in the absence of a substrate).

The parameters used in the analyses are shown in Figure 6. The line AB passes as nearly as possible through the spiracles (which are well-defined markers) and the hinge (F) of the ovipositor valves. Normal to this the line CD is drawn to pass through the extreme recurved tip of the lower ovipositor valve; CD cuts AB at point E. The angles of the opening of the ovipositor valves are defined by drawing lines (not shown on the diagram) from F to the extreme tips of the valves. The angles are then measured relative to AB. Point G is the position of the eighth abdominal spiracle. When the upper valve is below AB, the angle is recorded as negative. GE, GF, and the two valve angles were then measured on a series of prints of frames from the film. Figure 7a shows these four parameters plotted against frame number for a single cycle and Figure 7b the two important parameters plotted to show the cyclic nature of the movements.

Snodgrass (1935) has described the morphology of the ovipositor valves (Figure 8). The essential point is that the valves are hinged upon their own apodemes (Figure 8b) which carry intrinsic muscles (Figure 8a, nos. 271, 272, etc.) to the valves. Thus the ovipositor valves are capable of opening and closing without the need of muscles inserted into the wall of the abdomen (the tube at whose end the digging unit is situated) and the entire unit is free to move up and down the tube under the control of another set of muscles.

A simple interpretation of digging is that the ovipositor valves are thrust into the substrate (Figure 5, frames 1-4) and pull the abdomen after them as they open. This raises a number of problems; however, a major one being the question of what provides the reaction against the initial thrust of the valves.

The initial part of the thrust is directed ventrally by the ventral valve (Figure 5, frames 1-4), with a reaction to the thrust provided by the opposite side of the hole. A line bisecting the angle made by the ovipositor valves meets the dorsal part of the abdomen between segments VII and VIII: segment VIII is bulged upwards during digging and so presumably provides a base against which to push. This angular thrust has the effect of burying the ventral ovipositor valves into the substrate. At this point the valves start opening and the lower valves lever the digging unit along like an oar propelling a boat. At the same time the upper valves sweep open and push material away from the closed end of the hole.

This interpretation thus gives the upper and lower valves different functions, the lower being responsible for pulling the abdomen down the hole, the upper for excavation. If these were the sole movements to be considered the abdomen would not extend, since it would be pushed back up the hole on closure of the valves. However, the distance between spiracle VIII (point G) and the valve hinge F, is being reduced continuously throughout the cycle (Figure 7a), and on the return stroke of the valves this shortening compensates for the movement of the valves (Figure 7b) and keeps the distance EG approximately constant, so that although the valves and hinge move back up the hole, the part of the abdomen anterior to spiracle VIII does not. Thus the prime movers in the digging cycle are the ovipositor valves and the muscles which open and close them: the muscles which suspend them in the abdomen are of secondary importance.

The stronger set of these suspension muscles is that which thrusts the valves downwards at the start of the digging cycle (Figure 8a,c nos. 256 and 262). On the interpretation of the digging mechanism presented here, this set of muscles is required to ensure that the lower ovipositor valve gets a good hold on the side of the hole. The amount of movement of the valve assembly which these muscles produce in the isolated abdomen in Figure 5 is the maximum possible, and could probably occur only when the digging unit is moving freely down an already excavated hole. This type of movement is often observed whilst the locust is digging since the abdomen tip is repeatedly drawn a short way back up the hole and the ovipositor valves used to tamp down the sides of the hole, after which the digging unit ratchets its way back to the work-force of the hole (Vincent, 1975).

The opposing set of muscles (Figure 8a,c, nos. 248 and 263) is required to make sure that the ovipositor valves come back into the abdomen. However, it is conceivable that these muscles are also used to stretch the abdomen. The cross-sectional area of these muscles is about 0,015 cm^2. Taking a value of 1,0 to 1,5 Kg/cm^2 as the maximum force generated by such muscles (Nagai, 1970), the force available for pulling the abdomen down the hole is of the order of 15 to 25 g. Calculations based on data given by Vincent (1975) and Wood (1974) show that the force required to stretch the membranes of the abdomen is of the order of 12 to 15 g at the fullest extension. It is thus quite possible that these retractor muscles are also transmitting the pull of the ovipositor valve assembly to the rest of the abdomen.

2.4 PROPOSED ENGINEERING SOLUTION

The proposed engineering solution is based on the digging mechanism of the locust ovipositor. The goal is to develop a conceptual design of an excavating mechanism for non cohesive soils. The first step required to achieve such result was to model the digging mechanism of the locust in order to better understand the mechanics of such system. Two types of models have been developed: a physical model (University of Bath) and a numerical model (D'Appolonia).

The physical model developed by University of Bath represents the end part of the locust ovipositor. The model has been developed starting from a detailed analysis of the structure of a real ovipositor. Some photos of the ovipositor are shown in Figure 9.

The physical model has been developed in scale 1:16; the components and the main dimensions, upper and lower valves and apodeme tip are shown in Figure 10. The main components have been prototyped in plastic using stereolithography. The upper and lower valves and are hinged to the apodeme tip, and the connection has been obtained by using metallic clamps and plastic tape. A wooden stick is used to simulate the apodeme of the locust and two metallic wires are used to operate the two valves, simulating the action of the muscles and the tendons. The two artificial muscles can be operated simply pulling the extremities of the metallic wires synchronously or applying a value of force different at each end. By operating the muscles by pulling together the two extremities of the artificial muscle, the result is similar to what shown in Figure 11.

The starting position of the valves is shown in the first picture on the left had side of Figure 11. The valves are closed and the line ideally connecting the contact point of the two valves with the hinge lays at an angle of about 20 degrees with respect to the axial direction of the apodeme. When the valves start opening, the upper valve enters in contact with the lateral wall of the hole while the lower valve move away the soil from the bottom of the hole towards the opposite side. In the simulation of Figure 11 the lateral soil that would provide a reaction to the upper valve which, in turns, would aid the lower valve in its action, through the particular configuration of the hinge has not been modelled. In Figure 11 the sequence of the position of the tips of the upper and lower valve has been put in evidence by using marks, which allow to visualise their trajectory.

If we put an obstacle to the free movement of the upper valve, simulating the presence of the lateral soil, and we allow the system to move along the axial direction of the apodeme (hole) the trajectory of the tips of the two valves changes as depicted in Figure 12. In this case the mechanism moves forward of about 18 millimetres (calculated as the distance between the mark corresponding to the position of the tip of the lower valve at the beginning of the cycle and the mark corresponding to the position of the tip of the lower valve at the end of the cycle (see Figure 12).

The difference between the two trajectories of the tip of the two valves considering the simulation with and without external contact is visualised in Figure 13.

The physical model demonstrated to be very useful for the understanding of the mechanism. However it has some limitations, in particular it is difficult to measure the forces and reactions in the system to have a quantitative estimate of the performance of the system.

The numerical model developed by D'Appolonia has been conceived in order to simulate not the real structure, but the physical model. The model has been developed using DADS, a code for the multibody analysis. The scheme of the model with the main dimensions is shown in Figure 14.

The upper valve is modelled as a prismatic element (in blue in the figure) of length $48.5 \cdot 10^{-3}$ m, width $5 \cdot 10^{-3}$ m, and density 800 kg/m^3, with one revolute joint for the connection with the lower valve (revolute joint 2). The lower valve is modelled as a prismatic element (in red in figure) of length $59.5 \cdot 10^{-3}$ m, width $5 \cdot 10^{-3}$ m, and density 800 kg/m^3, with two revolute joints for the connection with the apodeme (revolute joint 1) and the upper valve (revolute joint 2). The thickness of the three components is $3 \cdot 10^{-3}$ m. The definition of a prismatic joint between the apodeme and the ground allows the translation of the system in horizontal direction (x-axis) (Figure 15).

Two "point-to-point" contact types have been defined to take into account, respectively, the contact between the apodeme and the lower valve that occurs when the lower valve has achieved the maximum opening angle and the contact between the upper valve and the ground. The effect of the contact between the lower valve and the soil at the bottom of the hole has been simulated using a viscous force proportional to the relative velocity between the apodeme and the lower valve, applied at the tip of the valve with direction tangential with respect to the rotation around the revolute joint 1. Figure 16 shows the variation of the force versus time.

The muscles have been simulated by applying two time-dependent forces of equal intensity between the apodeme and the two valves, as depicted in Figure 14. Figure 17 shows the Force diagram vs. time.

The results of the simulation are shown in Figure 18, starting from time t=0.0040 s (Figure 18 a), corresponding to the starting position of the mechanism. In Figure 18b (t=0.0250 s) the upper valve enters in contact with the external contact representing the lateral soil. Direction and versus of the reaction force is visualised with the blue arrow in Figure 18b and its variation versus time is shown in Figure 19. It can be seen that after an initial high value corresponding to the impact and some fluctuation due to the sliding of the upper valve tip around the external contact surface, the value of the force becomes almost constant and equal to $1{,}2 \cdot 10^{-2}$ N, up to time t=0,4260 s (Figure 18h) when the upper valve starts closing and the contact with the external contact surface opens. The ratio between the reaction force and the force applied by the muscles is $1{,}2 \cdot 10^{-2}$ N / $3{,}0 \cdot 10^{-2}$ N= 0,40, value that could be taken as the efficiency of the mechanism.

It can be seen that the contact between the lower valve tip and the internal contact surface is soft, and the two circles used to visualise the two surfaces in contact penetrate each other.

The upper and lower muscles are visualised by using cylindrical objects connecting the apodeme and the two valves, the volume of the cylinders being constant, so that to their shortening is visualised as an increase in diameter.

Figure 20 shows the results of the simulation in terms of advancing of the apodeme versus time. The model predicts a movement of about 18 millimetres of the physical model, corresponding to about 1,125 millimetres of the locust ovipositor per each cycle of opening and closing of the valves. Such prediction needs to be compared with the results obtained using the physical model and the real data.

Figure 21 shows the prediction of the digging velocity versus time of the mechanism, which is almost constant for time between 0,10 s and 0,40 s with a value of about 4,00 cm/s. The velocity drops after 0,4 s, when the upper valve starts closing and the contact with the external contact surface opens (the reaction force at the upper valve tip, acting as a propelling force became zero and the mechanism slows down). The comparison between the angular velocity of upper and lower valves versus time is shown in Figure 22.

The proposed engineering solution implementing the finding of the study is depicted in Figure 23. The idea is to conceive a reciprocating mechanism composed by a pair of cylindrical elements which rotate around their centres, with different versus of rotation, powered by electrical motors, linked together and joined to a third point which is free to rotate. The two cylindrical elements are provided with tooth (shaped like the valve of the locust?) to be designed to remove the soil from the bottom of the hole, carry it and partially pushing it towards the wall of the hole, and discharging it in the upper part of the mechanism. A solution for the removal of the soil particles could be of using a couple of brushes rotating around two axes parallel to the hole central axis.

The position of the tooth in the rotating elements is out of phase, that is when a tooth in one element is in contact with the soil at the bottom, there is no a tooth in this position in the other element. The tooth are reciprocating digging in the bottom of the hole and pushing the soil towards the lateral wall of the hole and the expected effect, depicted in Figure 23, is an alternated motion of the mechanism which, in analogy with the digging mechanism of the locust ovipositor, helps the mechanism to proceed into the soil.

3 CONCLUSIONS

The work performed in the framework of the Bionics and Space System Design has lead to the identification of four case studies which have been analyzed and described in the previous chapters. Based on the different and complementary expertise of the Biomimicry Expert Group, D'Appolonia has assigned each of the case studies selected by ESA to a different working team. In order to facilitate the management activities, a responsible has then been selected within each working group. The work has lead to a better understanding of the biological principle, together with a first attempt of an engineering solution.

Concerning "deployable digging mechanism for sampling below planetary surfaces", the biological principle analysed is the digging ovipositor 'valves' of the female locust. The upper valves lever the digging unit along like an oar propelling a boat and, at the same time, the lower valves sweep open and push material away from the closed end of the hole. The mechanism has been studied by developing a physical model of the digging apparatus of the locust and by numerical simulation of the physical model using a multibody code. The findings of the study provide an insight to the functioning of the locust apparatus, and suggested the possibility to develop an innovative digging system composed by two reciprocating rotating elements.

RDL/DMZ/SMC/AB:ad

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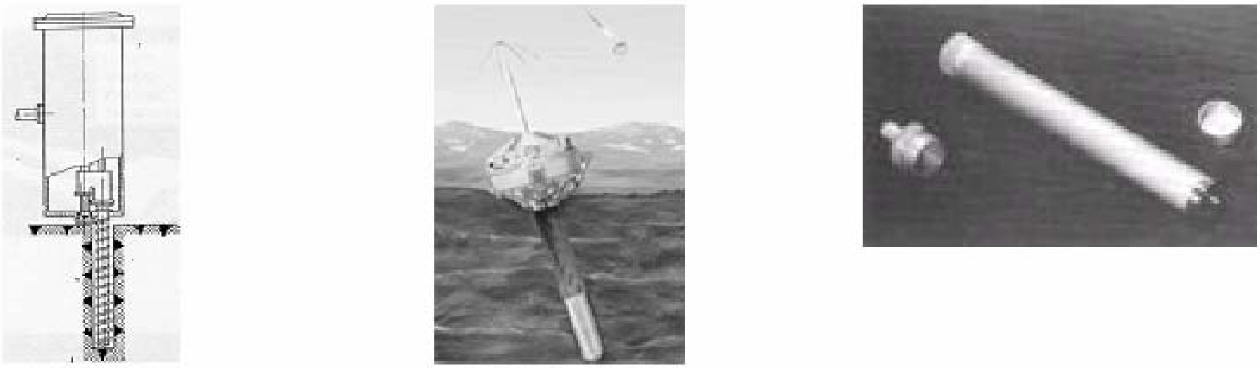
a) Viking Scoop (Image: NASA)

b) Tongs/pincers (MEE image: ESA)

c) Drag-lines, buckets or nets



d) Driller and corer (Luna 16 & 20 drill image: [74])

e) Penetrators and moles (Deep Space 2 image: NASA)

f) Drive tubes from Apollo missions (Image: NASA)

FIGURE 1

A BRIEF OVERVIEW OF SOME POSSIBLE
SAMPLING METHODS

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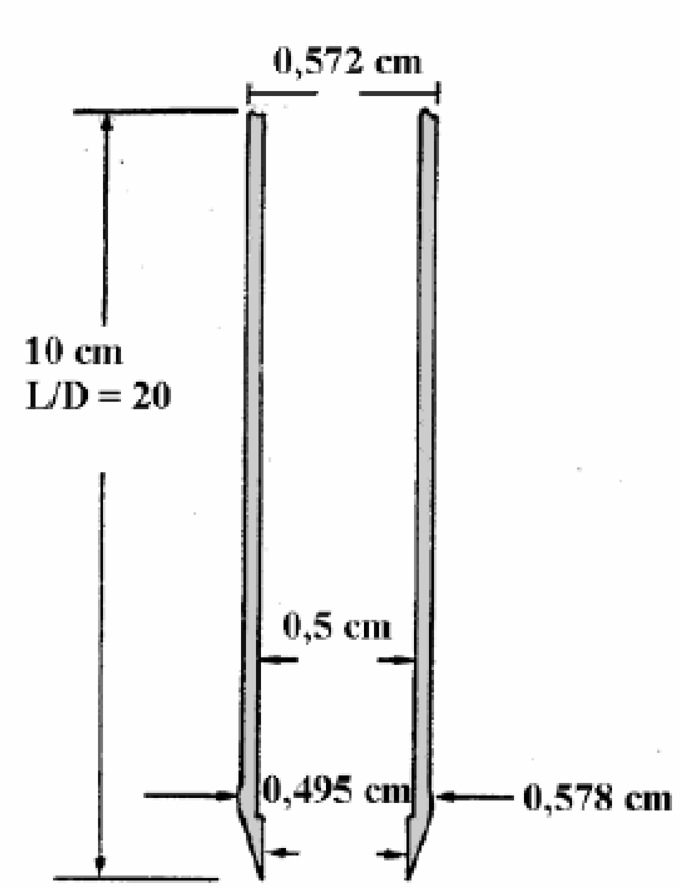

FIGURE 2

A DRIVE TUBE DESIGN. 'L/D' STANDS FOR 'LENGTH-PER-DIAMETER' –RATIO

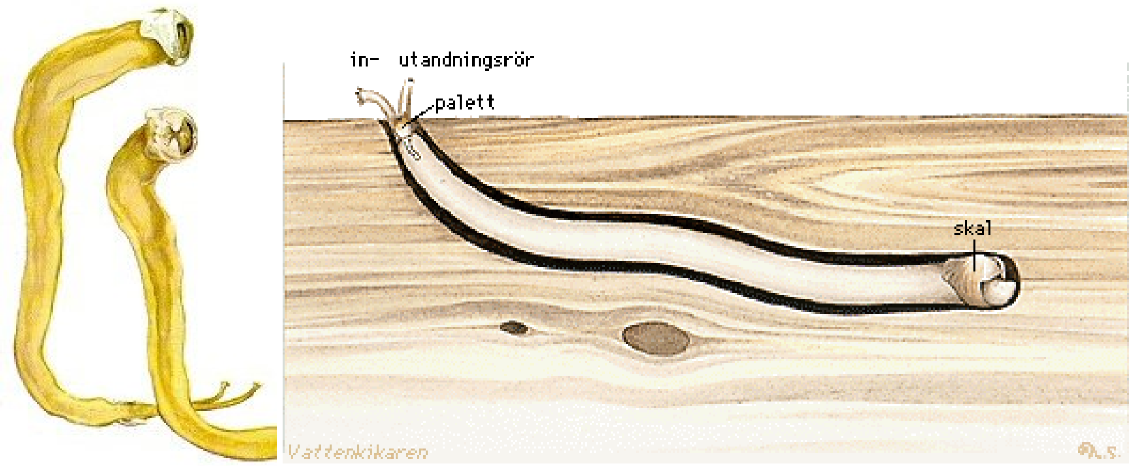

FIGURE 3

TEREDO WORM

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FIGURE 4

PHOLAS WORM

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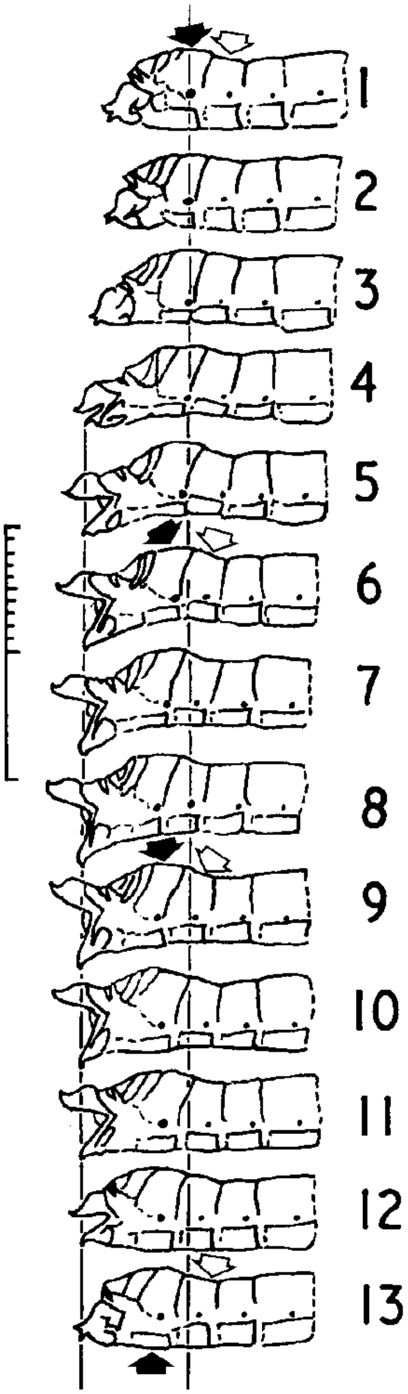

FIGURE 5

ACTION OF THE OVIPOSITOR VALVES OF THE FEMALE LOCUST

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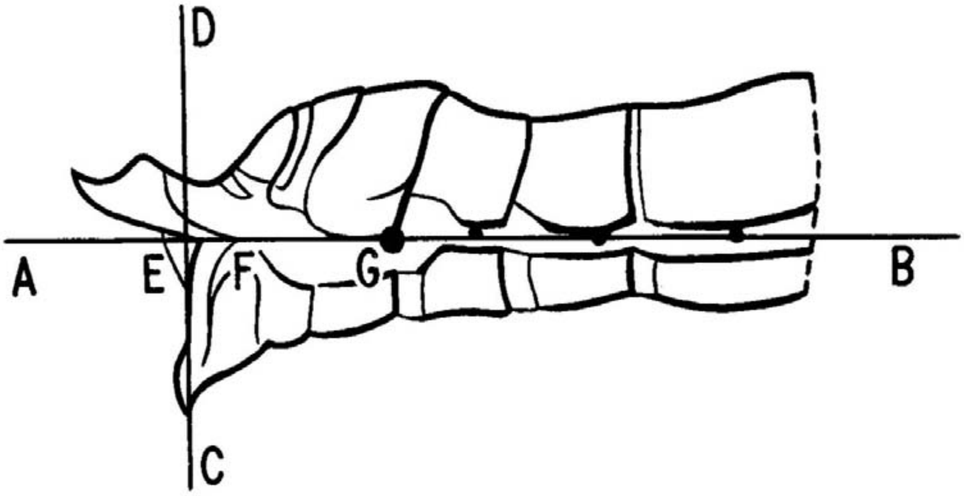

FIGURE 6

THE GEOMETRICAL CONSTRUCTION USED TO DERIVE THE DATA SHOWN IN FIGURE 7

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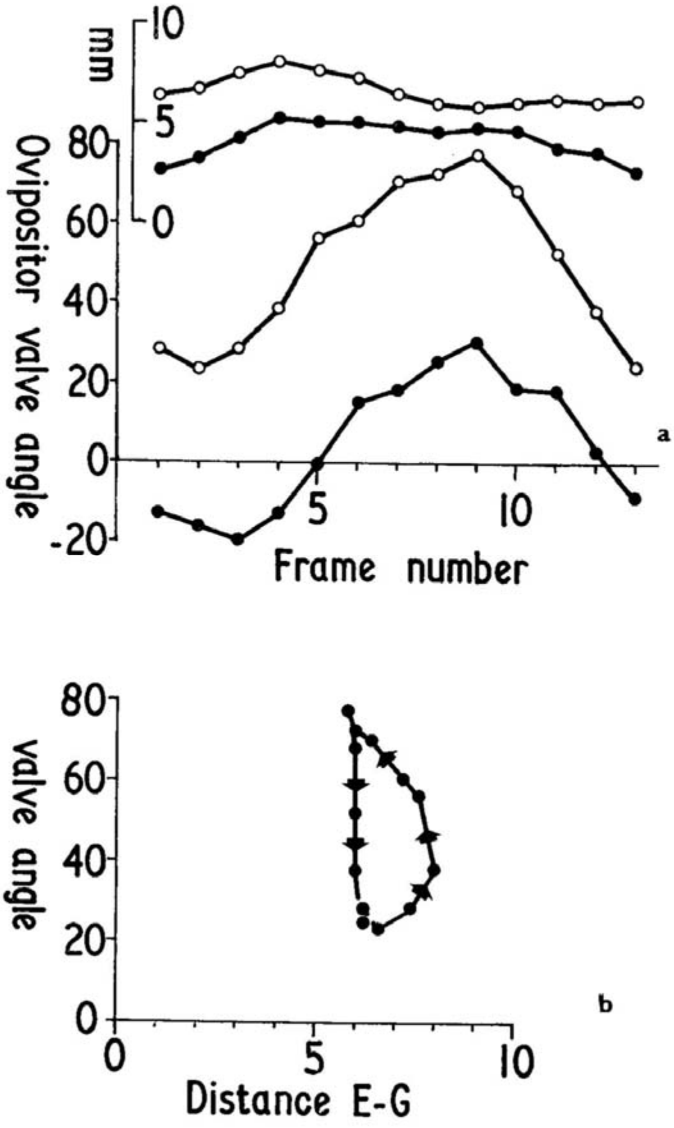

FIGURE 7

(A) UPPER TRACES-DISTANCE E-G (OPEN CIRCLES) AND DISTANCE F-G (CLOSED CIRCLES) IN MILLIMETERS. (B) THE CYCLE OF MOVEMENT OF THE OVIPOSITOR VALVES. ALL ANGLES ARE IN DEGREES

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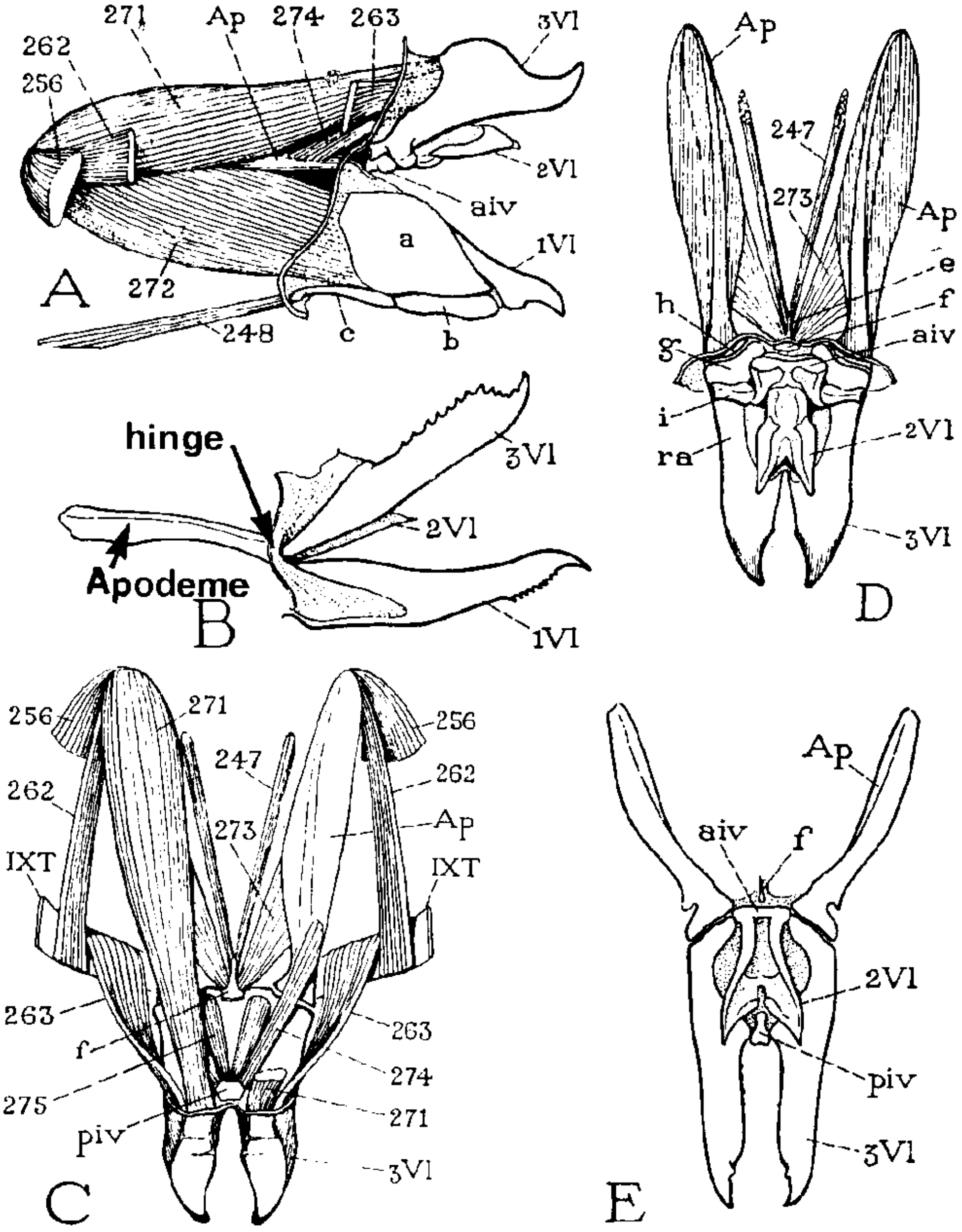

FIGURE 8

MORPHOLOGY OF THE OVIPOSITOR
VALVES AND MUSCLES OF TYPICAL
GRASSHOPPERS (SNODGRASS, 1935)

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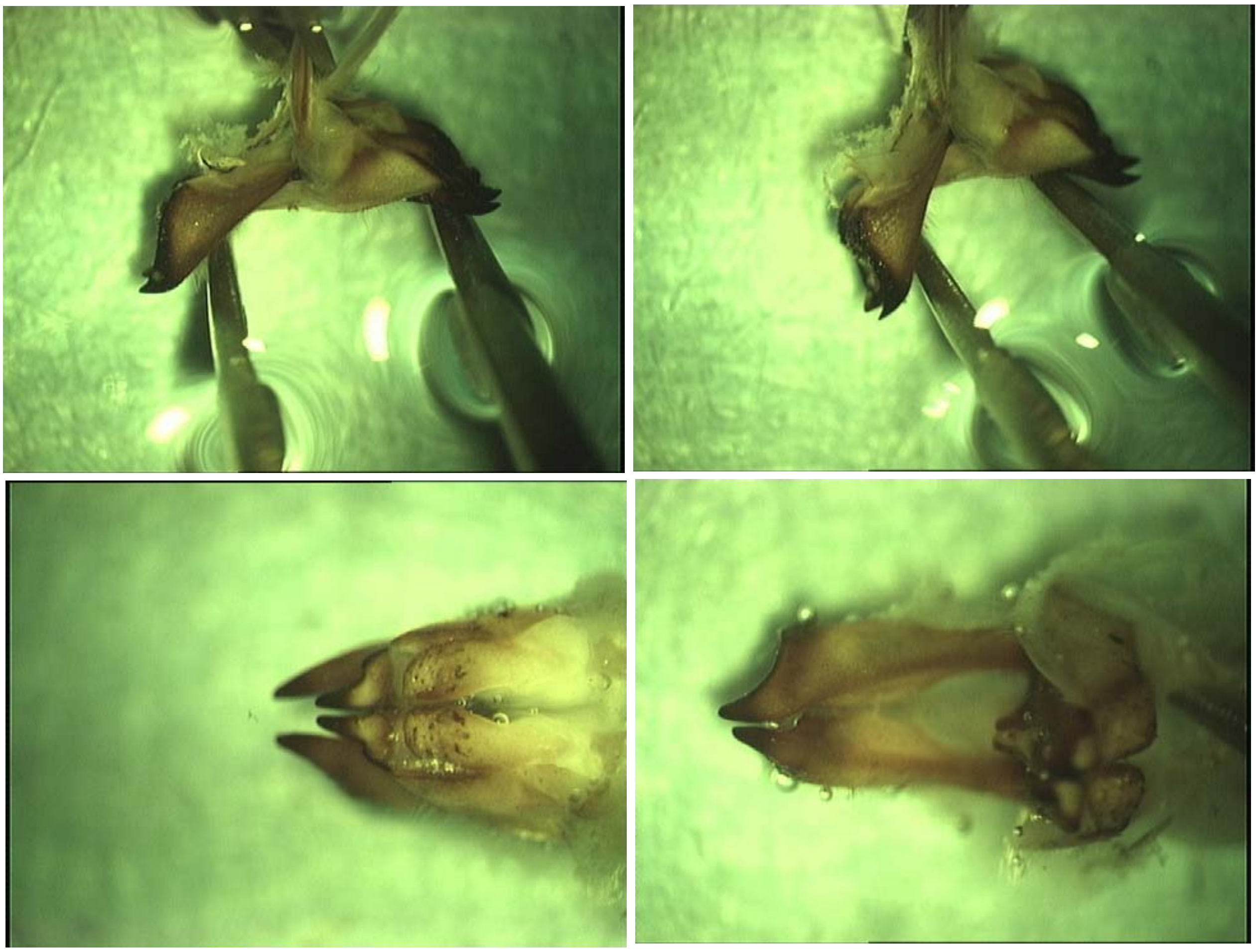

FIGURE 9

PHOTOS OF THE OVIPOSITOR FROM DIFFERENT ANGLES OF VIEW

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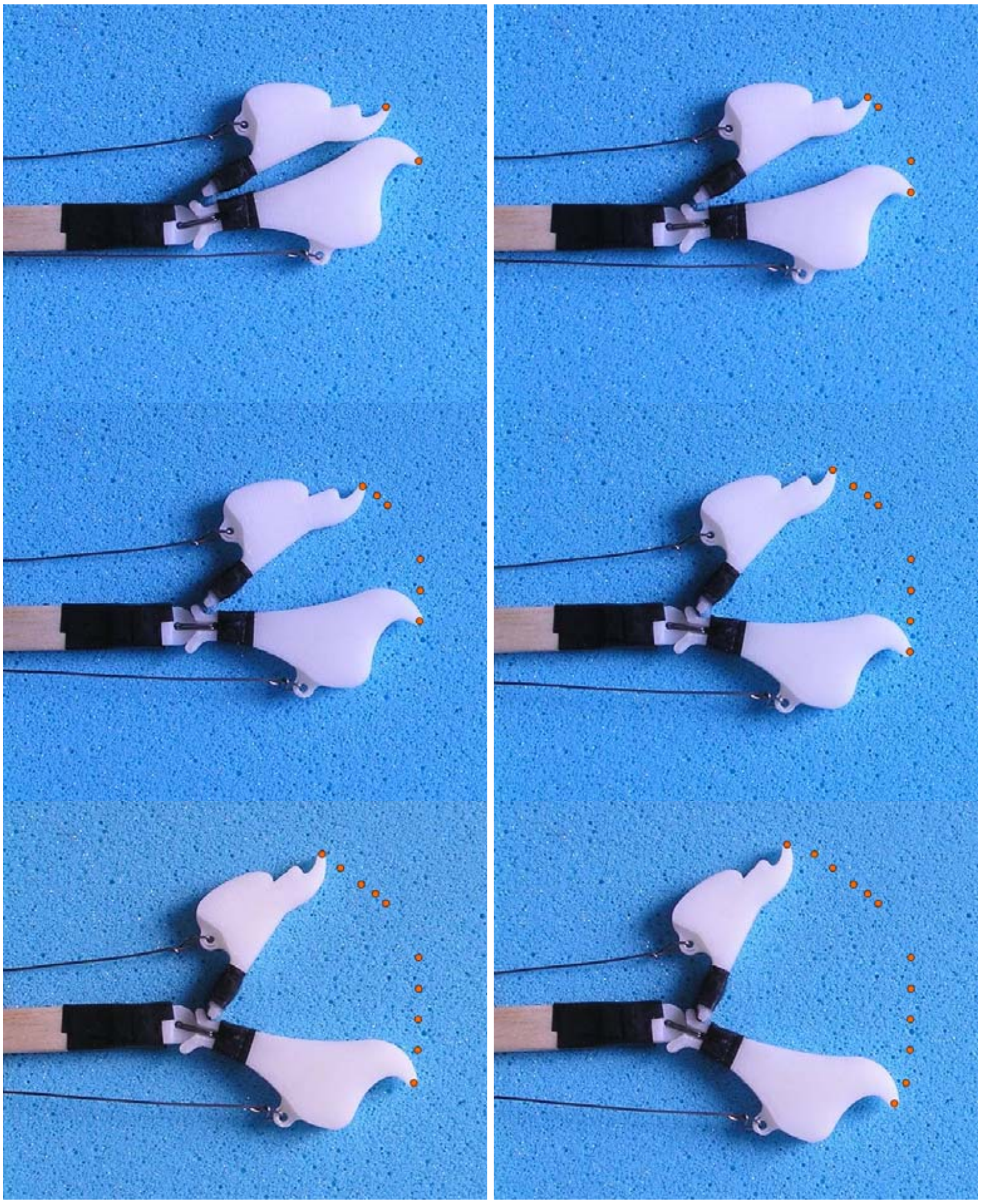

FIGURE 10

PHYSICAL MODEL OF THE LOCUST OVIPOSITOR

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Noordwijk, The Netherlands

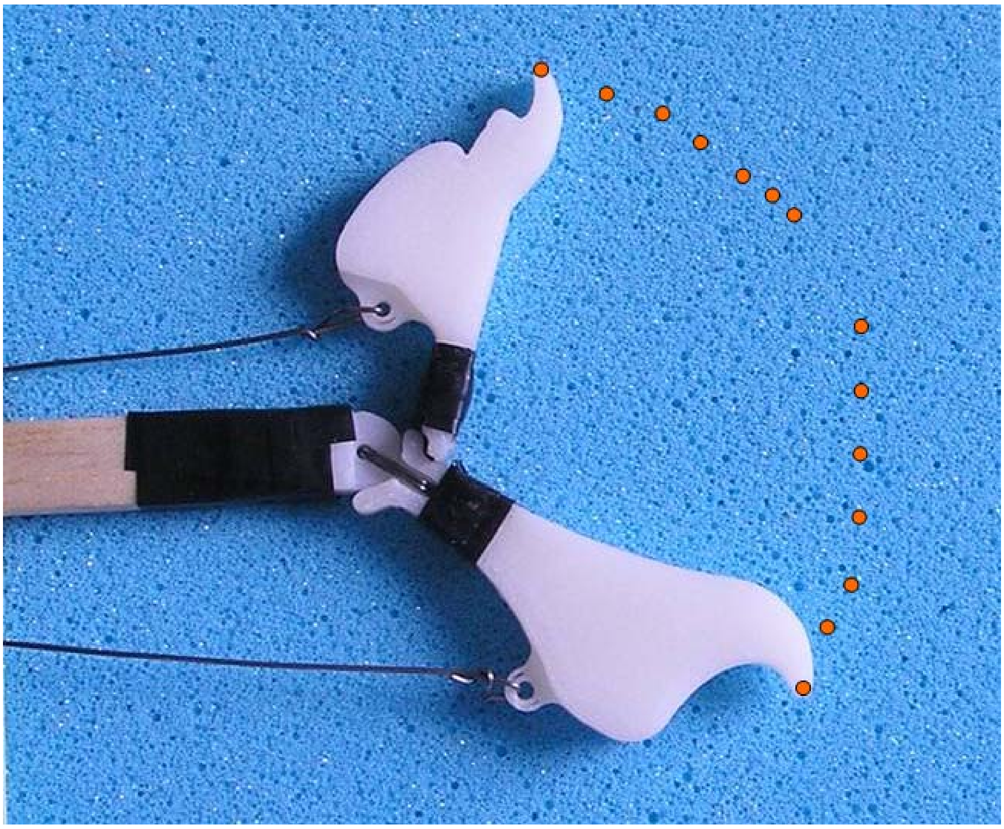

FIGURE 11

SIMULATION OF LOCUST DIGGING
MECHANISM USING THE PHYSICAL
MODEL, WITHOUT EXTERNAL CONTACT

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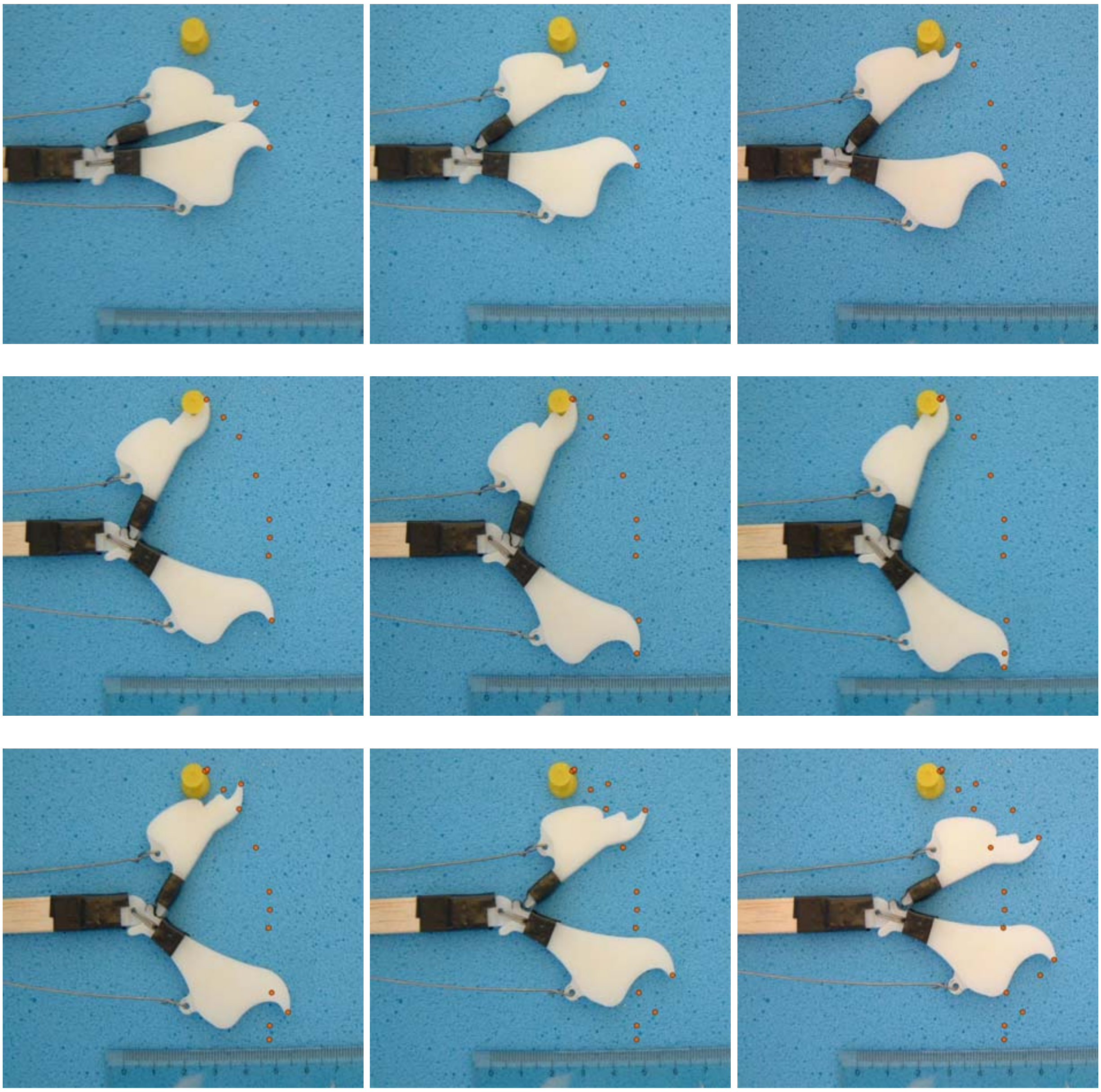

FIGURE 12

SIMULATION OF LOCUST DIGGING MECHANISM USING THE PHYSICAL MODEL, WITH EXTERNAL CONTACT

PREPARED FOR

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Noordwijk, The Netherlands

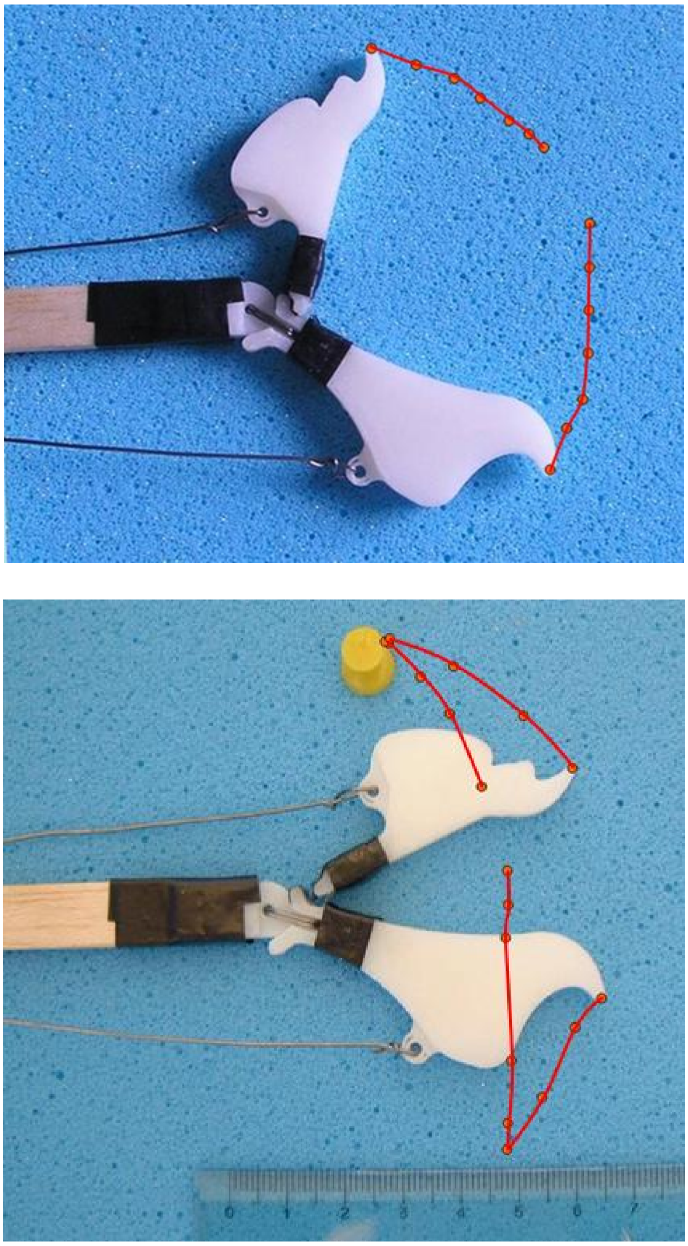

FIGURE 13

COMPARISON BETWEEN THE TWO TRAJECTORIES OF THE TIP OF THE TWO VALVES CONSIDERING THE SIMULATION WITH AND WITHOUT EXTERNAL CONTACT

PREPARED FOR

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Noordwijk, The Netherlands

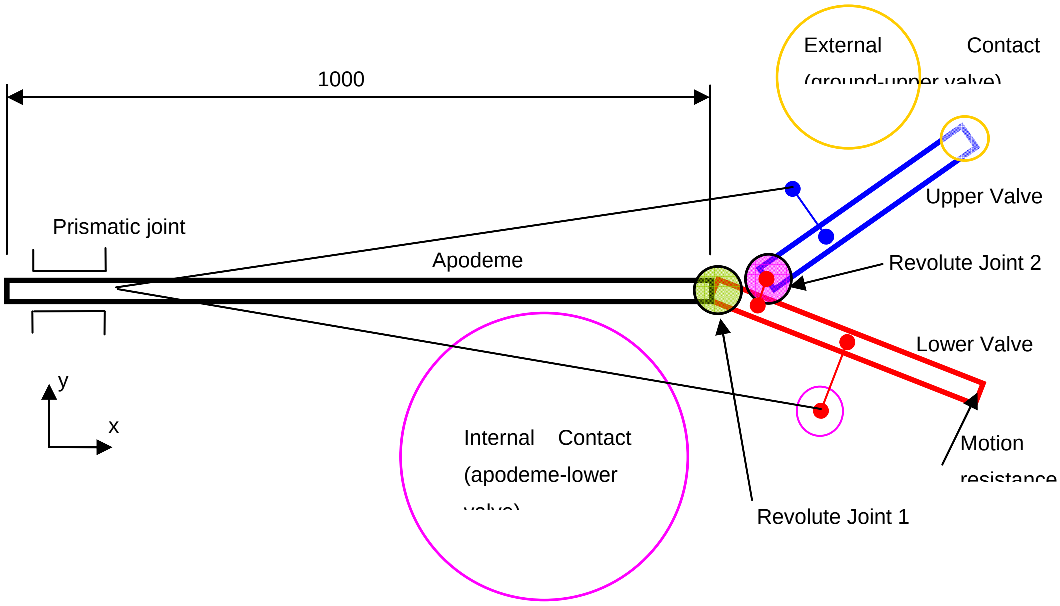

FIGURE 14

SCHEME OF THE MULTIBODY MODEL
(MEASURES IN MILLIMETRES)

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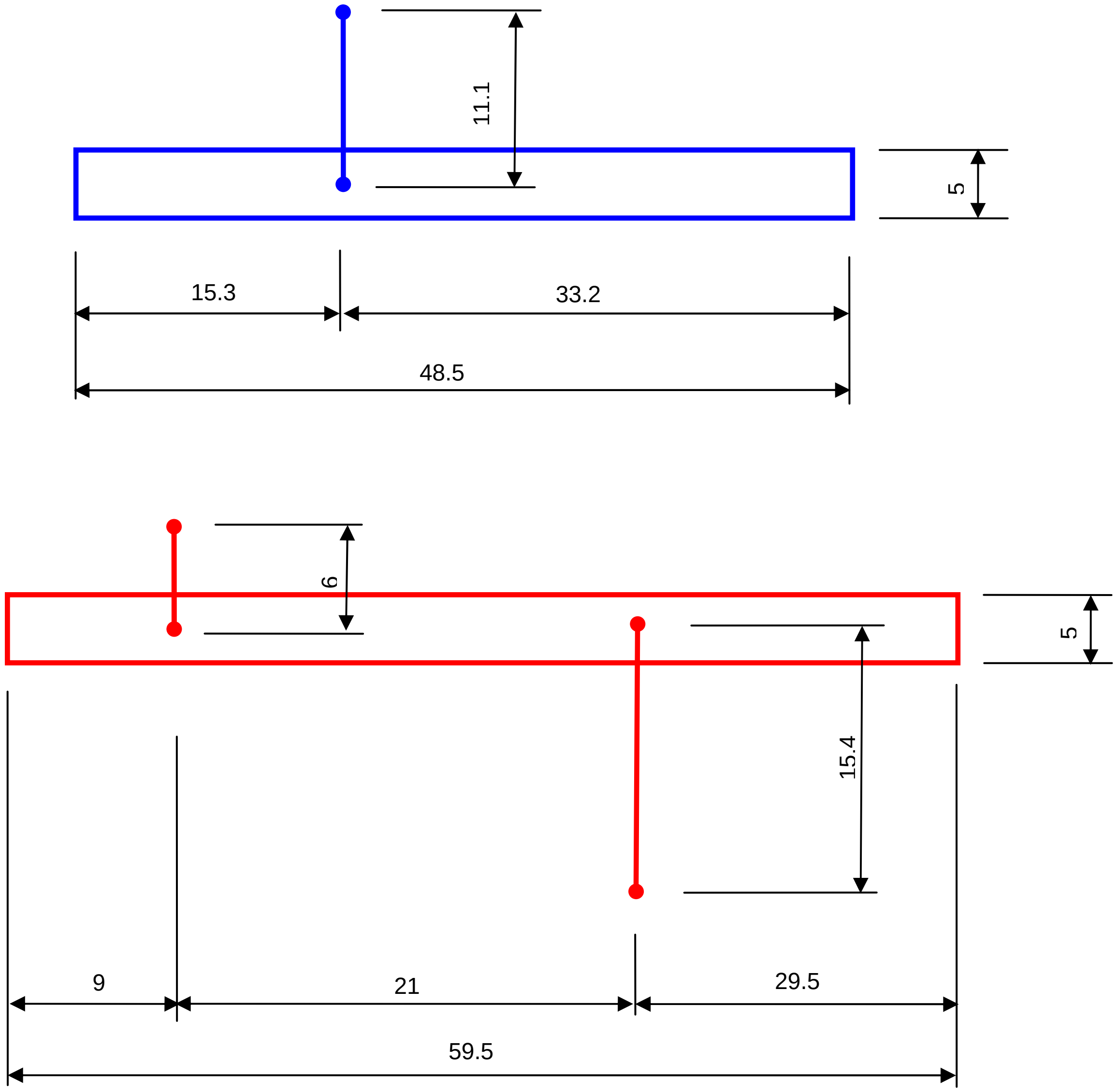

FIGURE 15

UPPER (BLUE) AND LOWER (RED) VALVES
(MEASURES IN MILLIMETRES)

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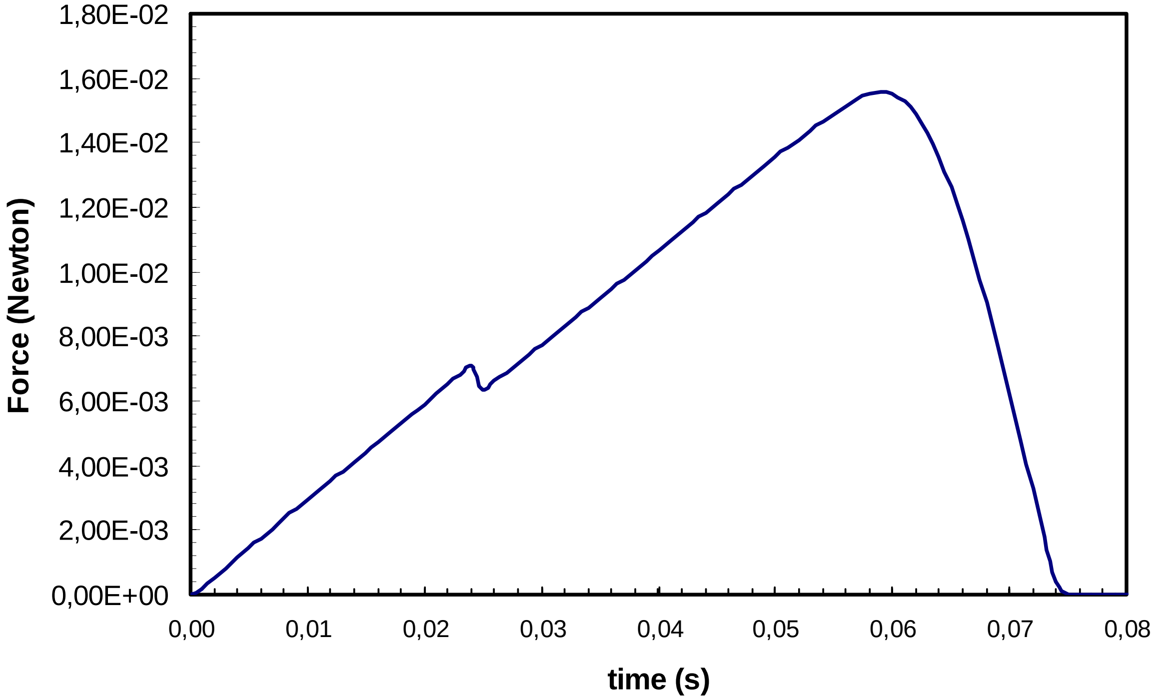

FIGURE 16

FORCE AT LOWER VALVE TIP

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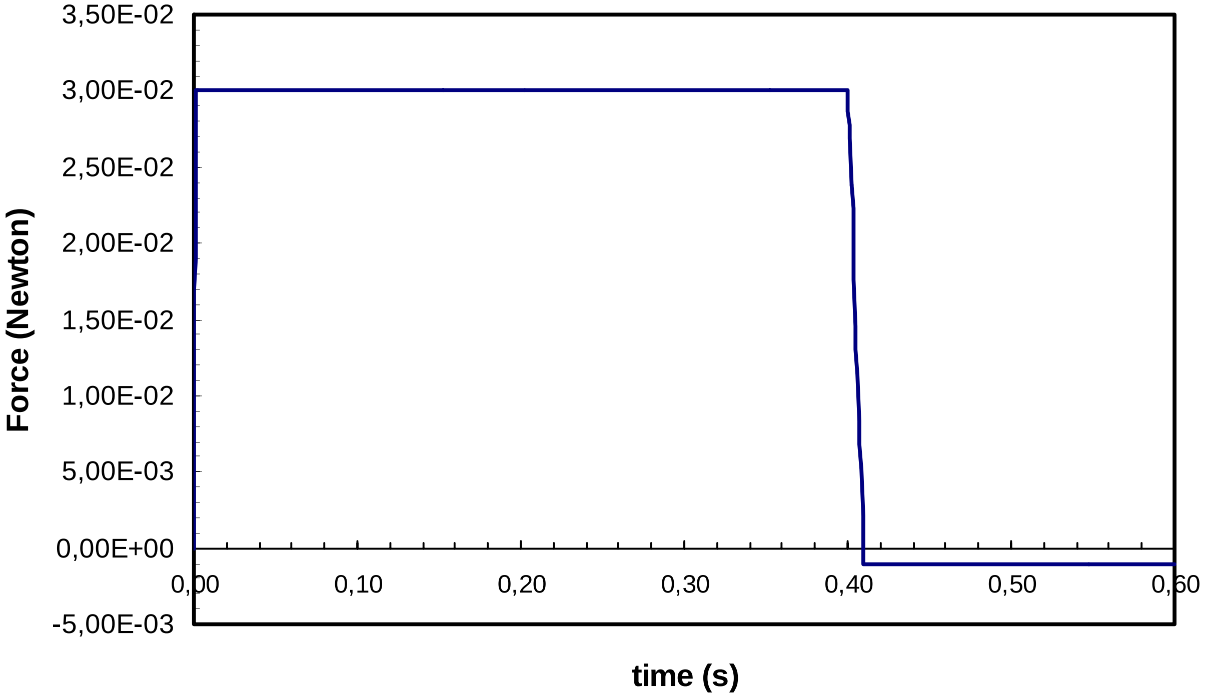

FIGURE 17

FORCE IN THE MUSCLES VS. TIME

PREPARED FOR

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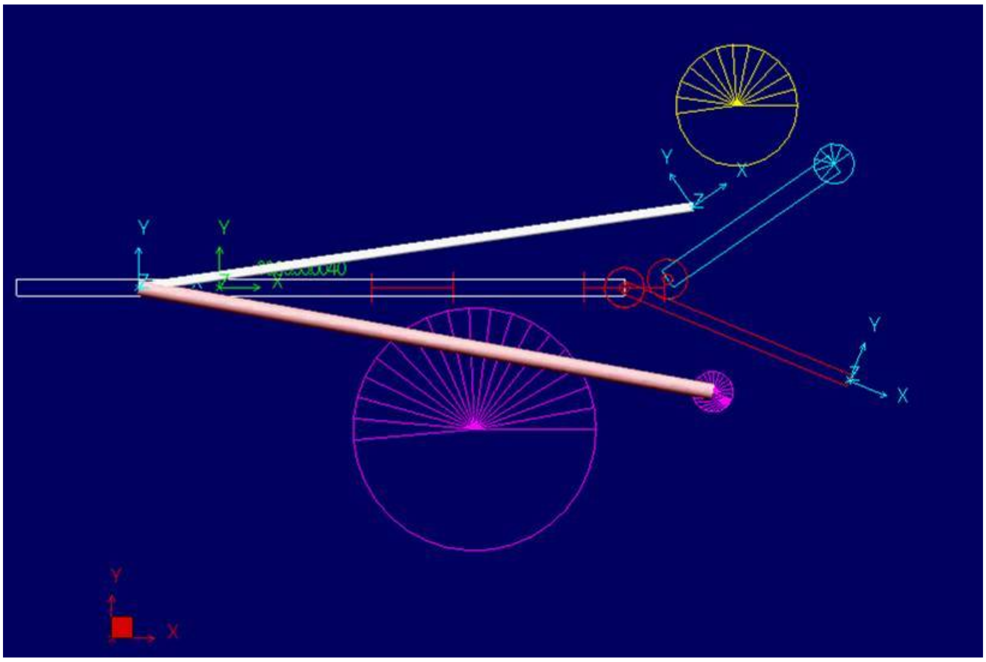
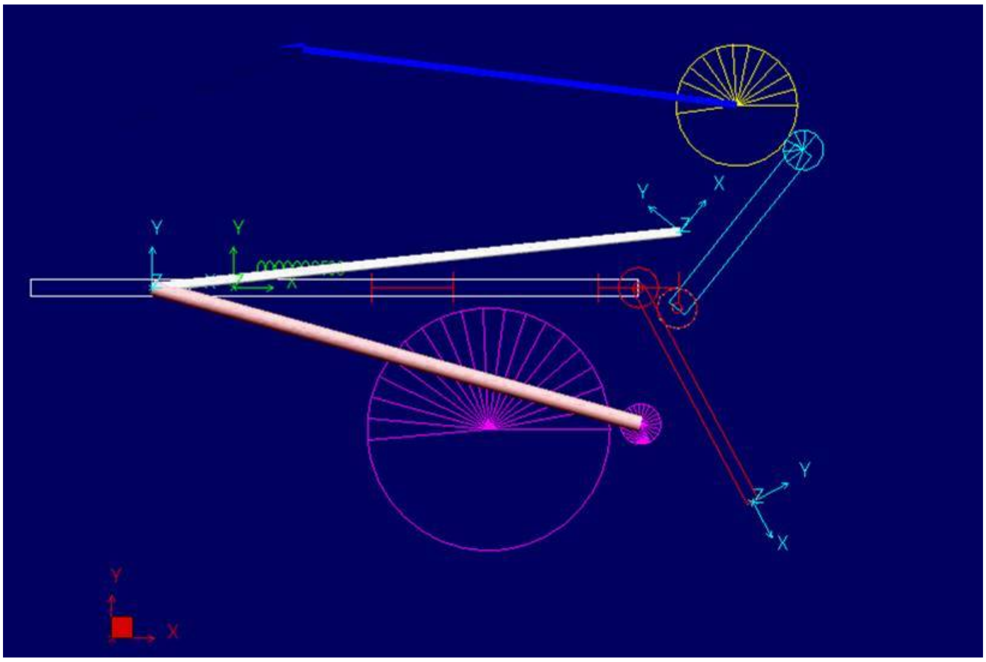
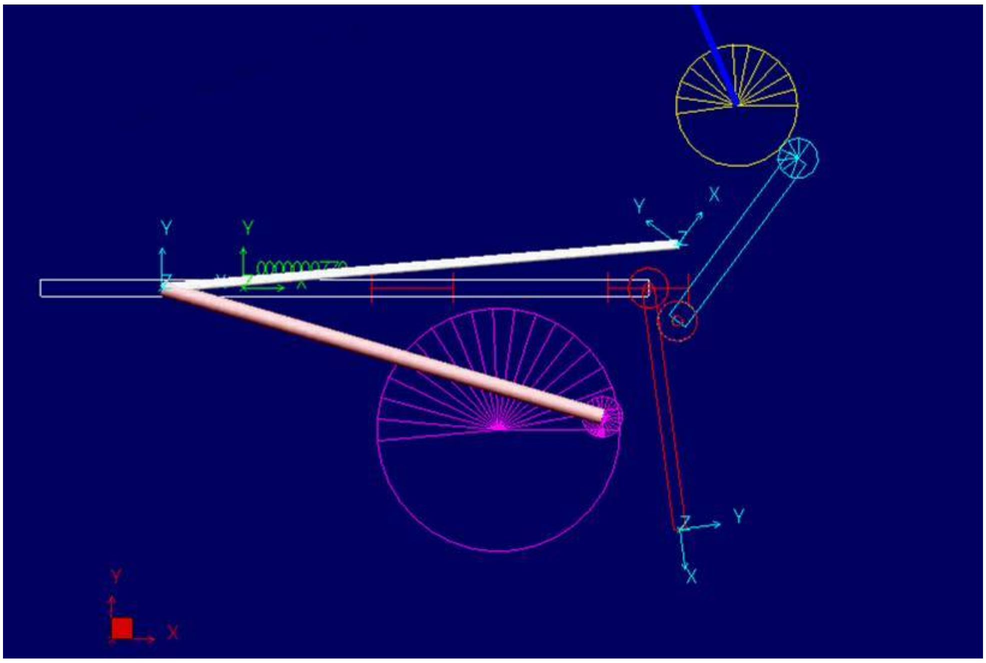
Noordwijk, The Netherlands



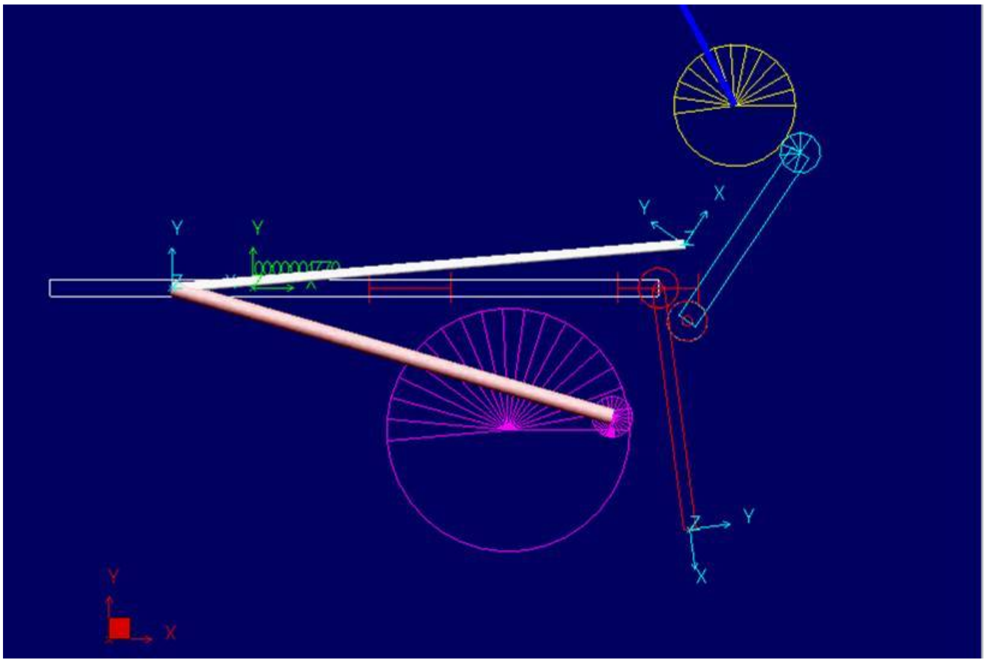
a) t=0.0040 s



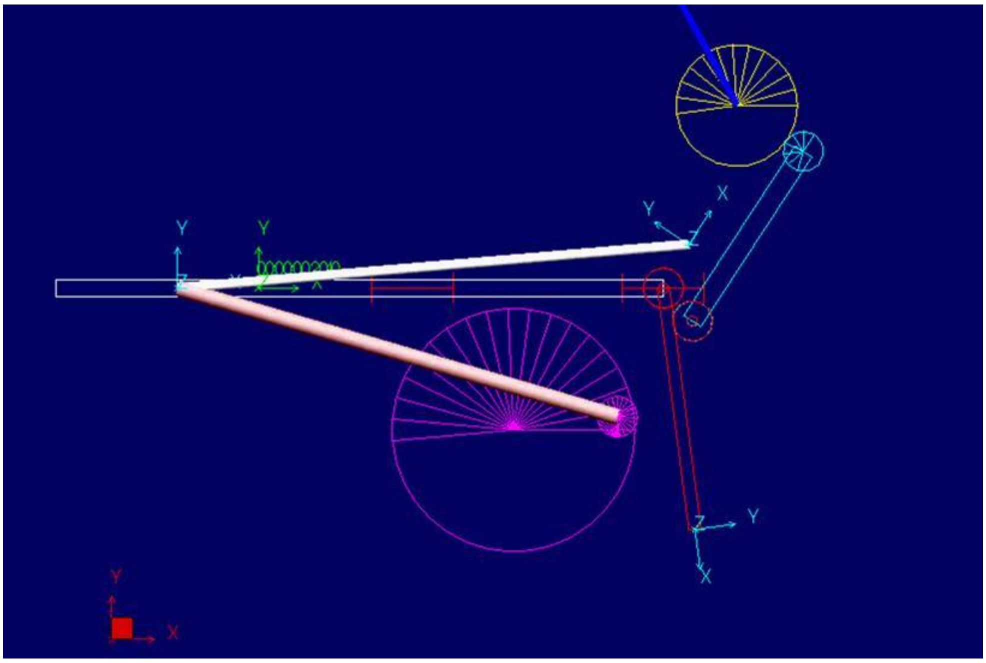
b) t=0.0250 s



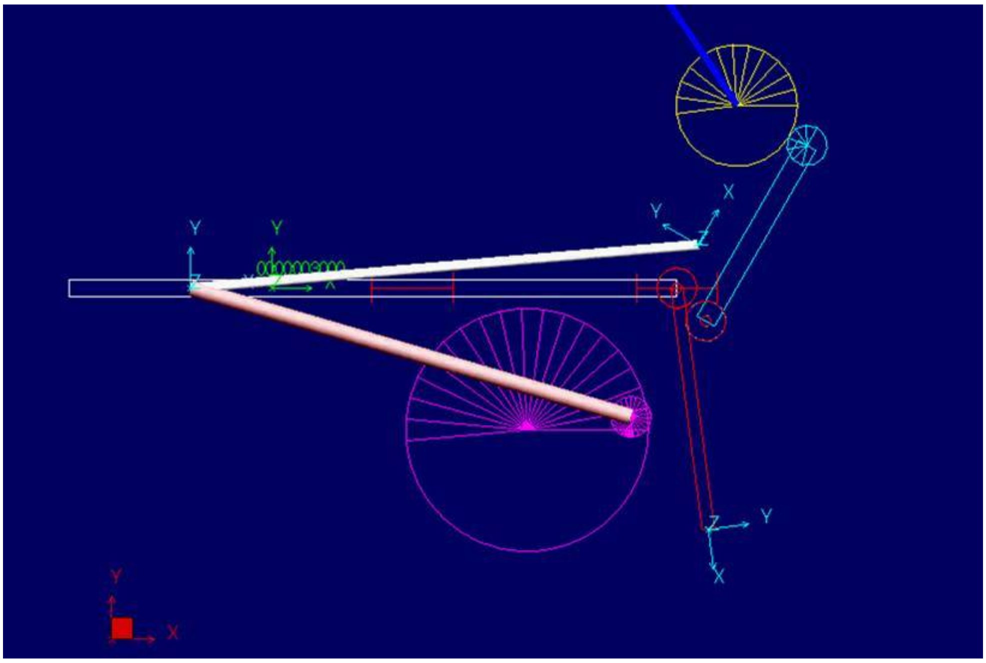
c) t=0.0330 s



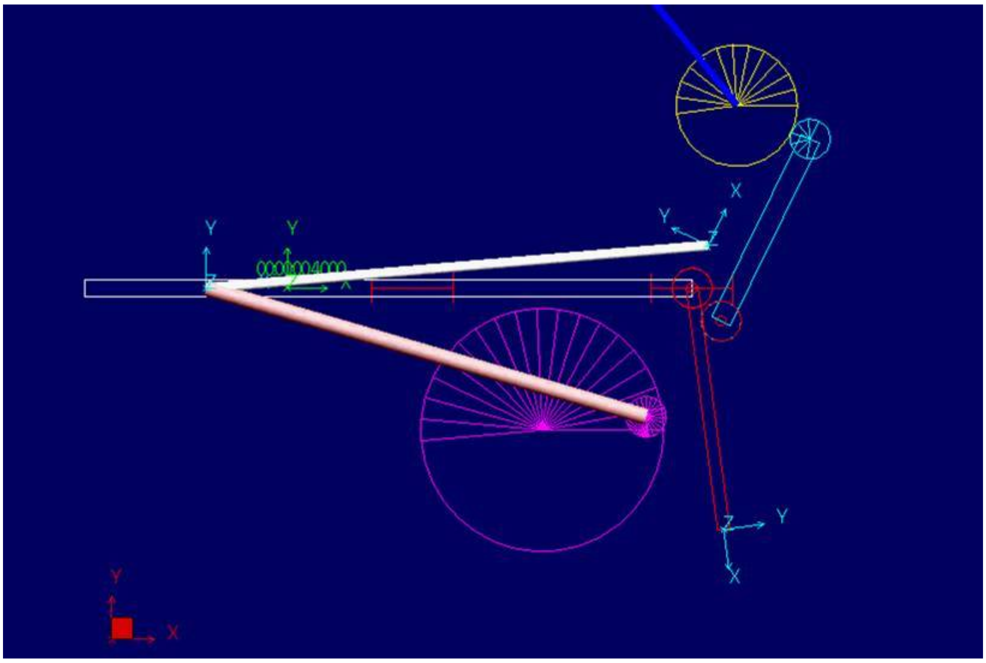
d) t=0.1770 s



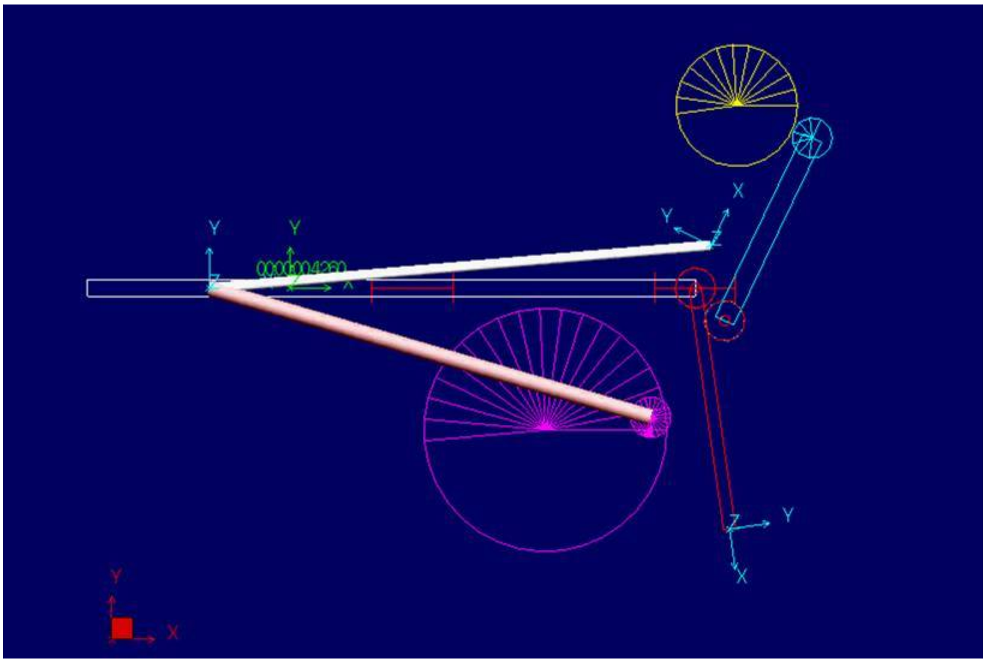
e) t=0.2000 s



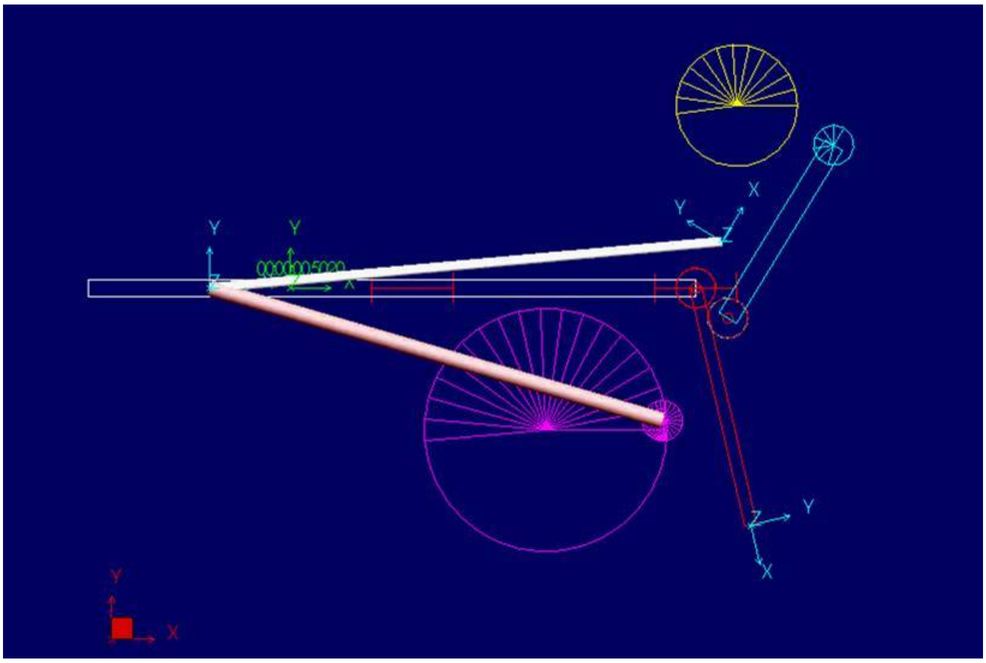
f) t=0.3000 s



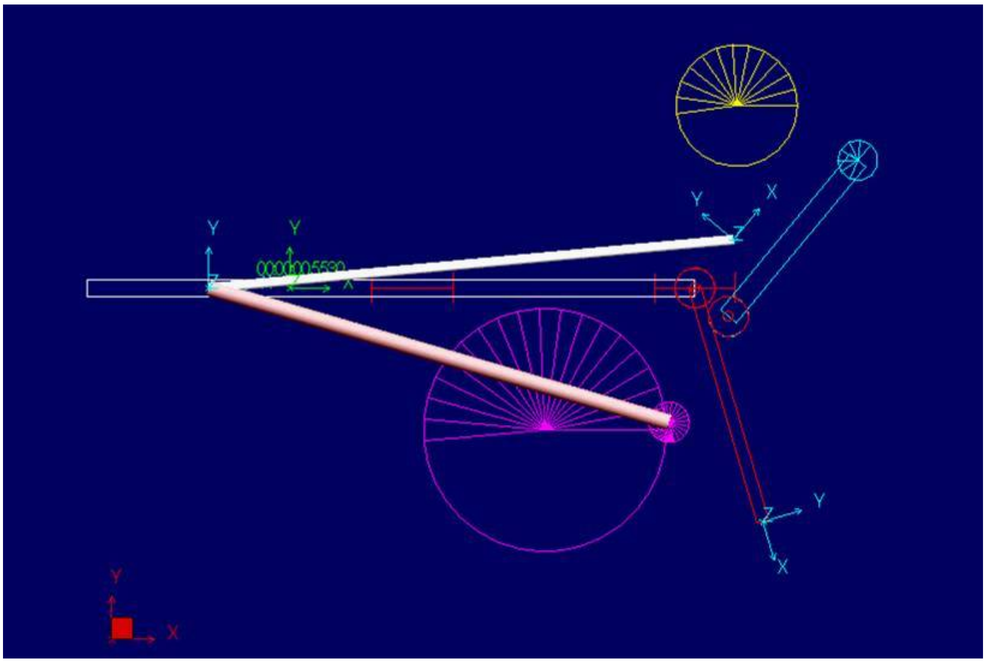
g) t=0.4000 s



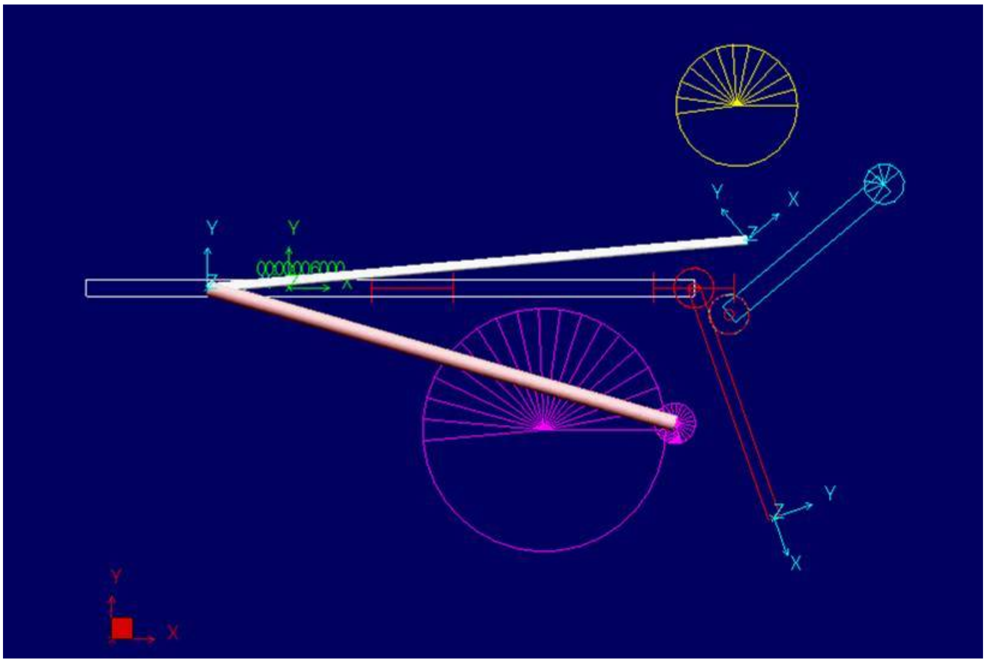
h) t=0.4260 s



i) t=0.5020 s



j) t=0.5530 s



k) t=0.6000 s

FIGURE 18

SEQUENCE OF THE SIMULATION OF THE
MULTIBODY MODEL

PREPARED FOR

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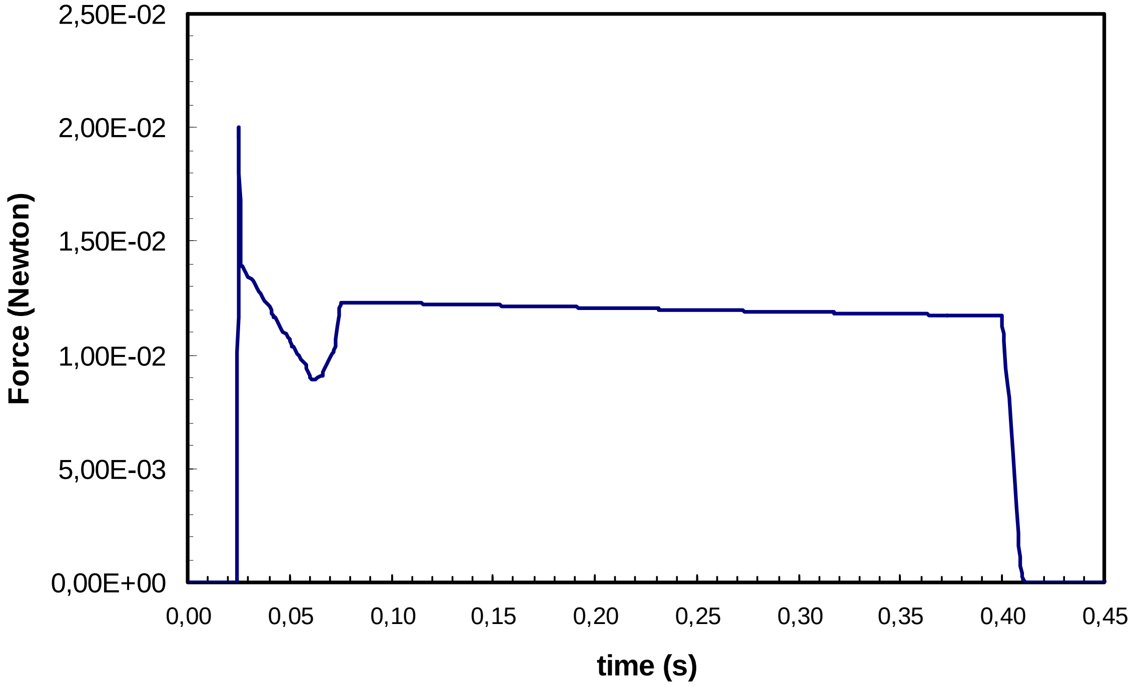

FIGURE 19

REACTION FORCE AT THE UPPER VALVE TIP VS. TIME

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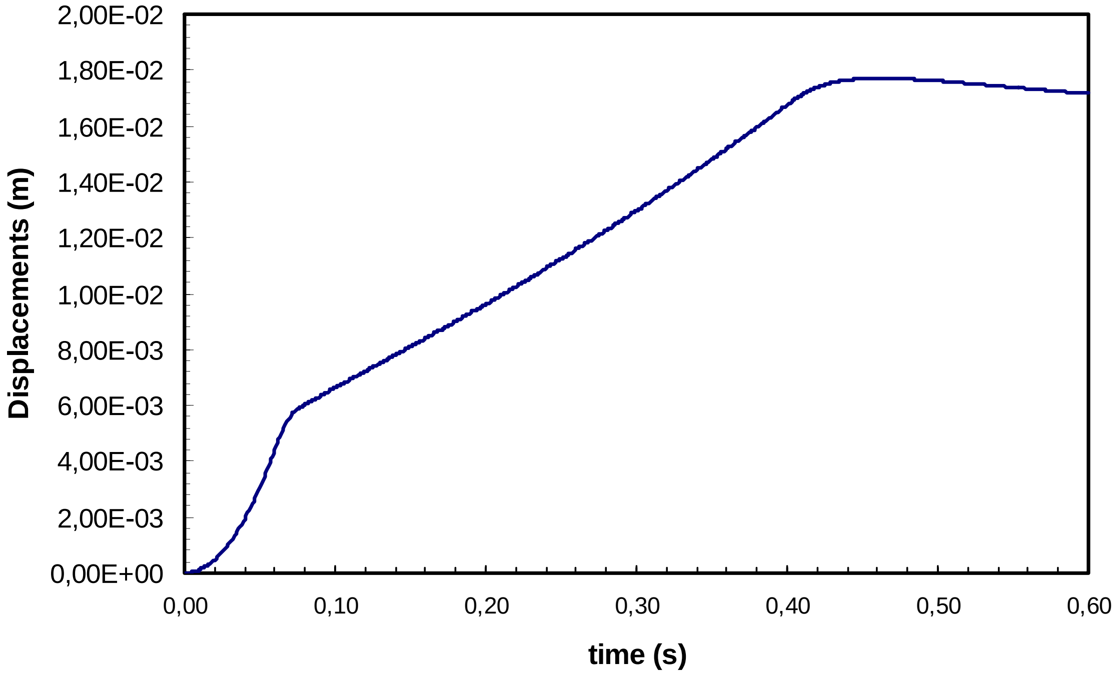

FIGURE 20

ADVANCING OF APODEME VS. TIME

PREPARED FOR

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Noordwijk, The Netherlands

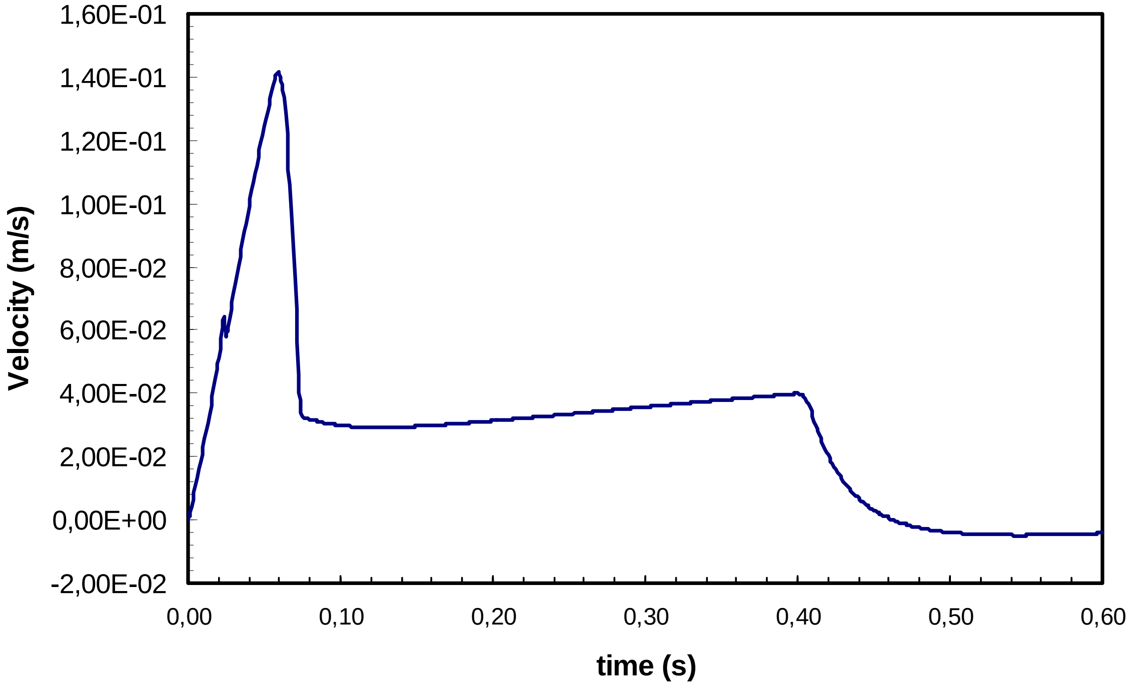

FIGURE 21

DIGGING VELOCITY VS. TIME

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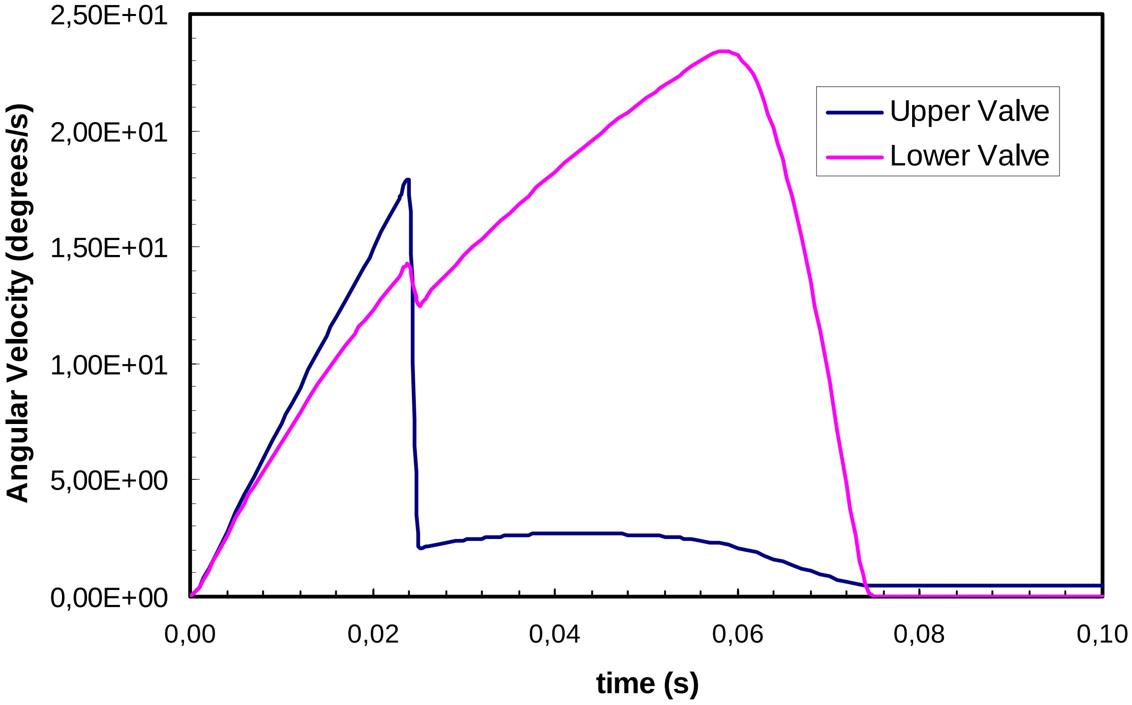

FIGURE 22

ANGULAR VELOCITY OF UPPER AND LOWER VALVES VS. TIME

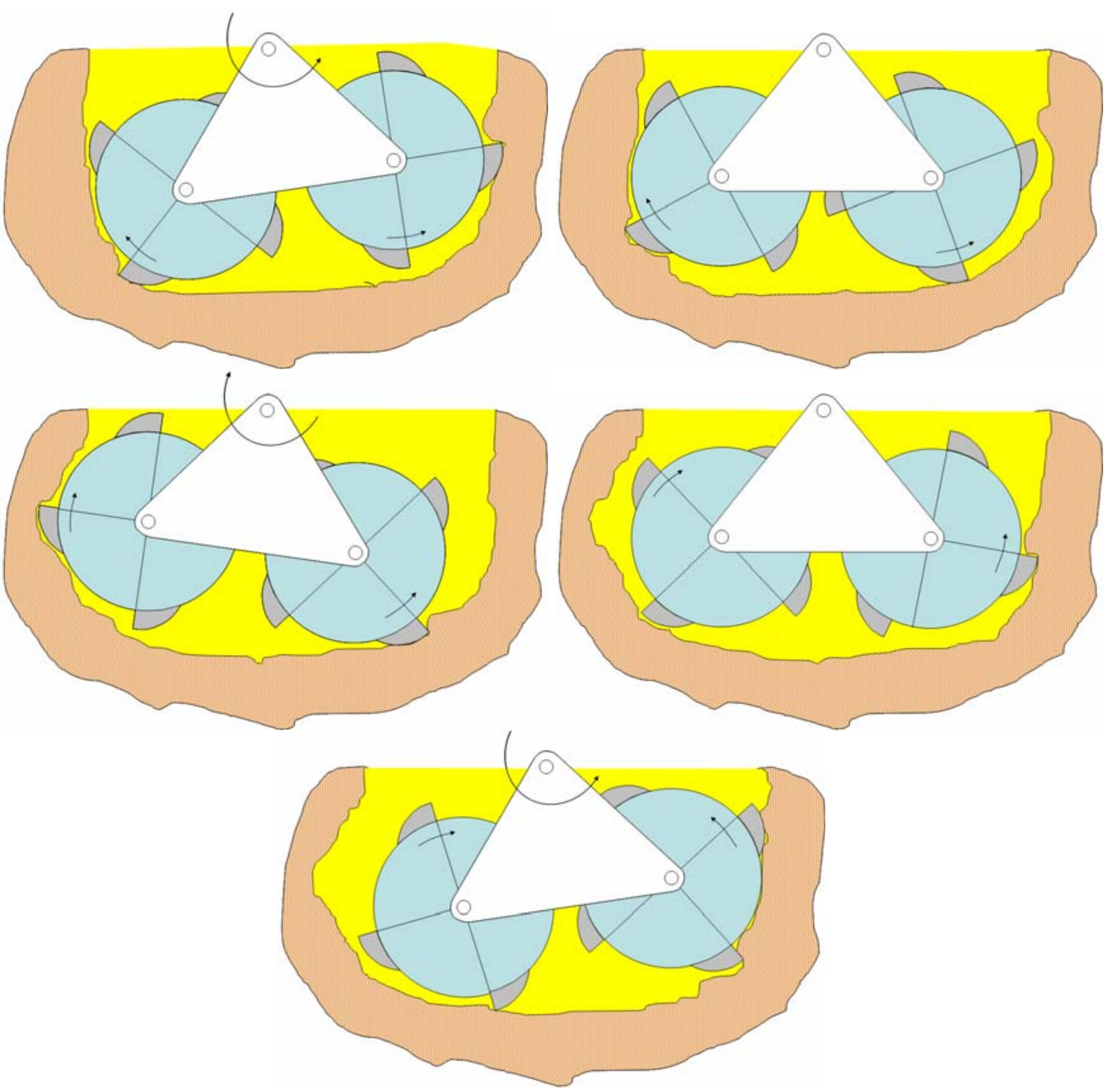

FIGURE 23

RECIPROCATING MECHANISM FOR
DIGGING INTO GRANULAR SOIL

PREPARED FOR

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Noordwijk, The Netherlands