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BIO-INSPIRED MICRO-DRILLS FOR FUTURE PLANETARY EXPLORATION

C. Menon
Advanced Concepts Team, ESA

J. F. V. Vincent,
University of Bath

N. Lan,
Advanced Concepts Team, ESA

L. Bilhaut,
Advanced Concepts Team, ESA

A. Ellery,
University of Surrey

Y. Gao,
University of Surrey

D. Zangani,
D'Appolonia

S. Carosio,
D'Appolonia

C. Manning,
University of Bath

M. Jaddou,
University of Bath

S. Eckersley,
EADS-Astrium

ABSTRACT

In a domain such as space technology, where robustness, mass, volume and power efficiency are key, biological organisms may provide inspiration for new systems with high performance. By using micro-technology processes, designers of space systems may take advantage of the millions of years over which miniaturised mechanisms in plants and animals have been optimised for survival. Space exploration often requires systems equipped with drills, and miniaturised drillers could enable a number of new space operations. Two natural digging systems have been studied as potential miniature space digging systems; the ovipositors of the female *locust* and of *sirex noctilio*, a species of woodwasp. Being insectoid systems, the mechanics of their design work on an inherently small scale, though they are also thought to be scalable. Results of preliminary studies, performed during collaboration between the Advanced Concepts Team of ESA, the University of Bath, the University of Surrey, D'appolonia and EADS-Astrium, are presented and discussed. Engineering solutions are proposed and analysed to assess the potential of new bio-inspired miniaturised digging systems for space applications.

INTRODUCTION

This paper presents and discusses the potential for innovative solutions and applications for bio-inspired, miniaturised drilling systems. A biomimetic study has been performed in order to find inspiration from nature in the design of novel mechanisms. In particular, two organic drills, which have been assessed in more detail, are presented and discussed. During a study carried out between the Advanced Concepts Team of ESA, the University of Bath, the University of Surrey, D'appolonia and EADS-Astrium, drilling mechanisms used by the woodwasp *Sirex noctilio* [29] and the female locusts, *Schistocerca gregaria* and *Locusta migratoria* [30] were identified being of particular interest for further development and were chosen as the subjects of more detailed preliminary studies [20, 21].

The following work describes digging mechanisms already developed for space applications and discusses the scope in potential for missions involving miniaturised drilling systems. The basic notions of biomimetics are presented and its relevance to the design of innovative systems is analysed. Two natural digging systems are described and engineered solutions based on these are proposed for future space missions.

DRILLING IN SPACE

Subsurface analysis is a growing requirement for space science missions for research in areas such as exobiology [10], study of the early solar system [8, 9], and the search for underground resources [10]. Some characteristics of underground material may be derived remotely, for instance using ground penetrating radar. Using this example, however, depth and resolution of data are limited by available power and the material under study [11, 13]. However, with direct contact the quality and amount of information able to be extracted may be increased sensibly. Impactor vehicles can be used in some cases to gain physical access to bodies' interiors, hitting them at hypervelociy, but are not always a feasible or desirable option. Drilling mechanisms still have the potential to offer an optimal choice when seeking range and fidelity of data acquisition across a broad spectrum of scenarios, whether for sample return or in situ analysis.

A BIO-INSPIRED APPROACH

For thousands of years, humans have been inspired by nature. In the engineering of systems, efforts have been made in recent years to formalise this process, attempting to systematically distil ideas useful for engineered systems from biological analogues.

In this way, biomimetics does not attempt to copy biological systems for the sake of it, nor to copy all of a system's characteristics directly. Rather, the key to successful biomimetic engineering is in finding biological systems that can in some way be useful in an engineering solution, then applying them at an optimal level of abstraction. When considering space systems, this is a salient point in the motivation of biomimetics, given that biological systems have evolved to survive in terrestrial environments very different to the vacuum of orbit or extraterrestrial surfaces. However many potential areas where biomimetic engineering could be of benefit in space have already been identified, with ever growing interest in the field [1-2].

Taking a high level view, there are abundant examples of biological systems that display characteristics that are desirable in space missions. These include robustness, adaptability, integration and autonomy all of which might be included in a biomimetically designed system.

Particularly relevant to this paper, however, it is the abundance of high-performance miniaturized systems that can be found in nature. The thousands of insect species, for example represent a vast resource of ready-designed systems, optimized through millions of years of evolution, using far less mass and volume than most conventionally engineered systems.

Advances in micro systems technology (MST) are enabling the conception of new solutions in space system design. The ability to use novel micro-fabrication techniques to produce devices with very small dimensions allows designers to consider the manufacture of new systems with a step change from conventional masses and volumes. Such drastic improvements may prove to be enabling for space missions, potentially allowing increases in mission capabilities or decreases in cost. Additionally, MST products give consistency in reproduction and provide opportunities for mass production. Applications involving large numbers of identical microsystems can be envisaged and have the potential to be realised at acceptable cost.

Not only do these technologies allow reduction in scale, however, greater integration of different functions in a small device could lead to entirely new mission designs. For biomimetics, MST is an enabling technology, allowing the application of ready-made, biological, highly integrated miniaturized systems in an engineered design.

REVIEW OF DRILLING SYSTEMS FOR SPACE APPLICATIONS

The following table summarises a selection of drilling systems designed and launched for use in space.

Table 1: A selection of drilling systems from past and ongoing space missions [14, 10]

Instrument	Mission	Mass (kg)	Approx. Volume cm^3	Power (W)
Luna 16/20 drills	Luna 16,20	13.6	-	140
Luna 23/24 drill	Luna 23,24	-	750000	-
Apollo drills	Apollo 11-12, 14-17	13.4	25000	3000
Viking scoops	Viking 1 - 2	11.3	49000	~200
DS2 micro-drill	Deep Space 2	<0.05	<11	<10
Philae SD2 drill	Rosetta	4.8	1100	230
Beagle-2 RCG	MEX/B-2	0.35	180	6
Beagle-2 PLUTO	MEX/B-2	0.34 (mole) 0.89 (total)	560	3
MER RAT	MER – A/B	0.7	110	5-10
Venera GZU drills	Venera 13-14, Vega 1-2	26.2	-	~35

The requirements and consequent parameters of each of the systems in Table 1 can be seen to be very different throughout the selection. Of course this is due not only to changing technology but also the particular mission objectives and environments, ranging from obtaining small soil samples close to the surface, to extracting rock cores from deeper down to avoid contamination from the surface environment.

Drilling methods may be broken down into the following categories [20] with particular advantages and disadvantages:

- Shaped charges – Ejection of molten metal to create a borehole can corrupt the environment both chemically and physically.
- Melting tip – The high powers required for this method and potential to corrupt the drilling environment generally make it unattractive for space applications other than drilling into ice.
- Rotary (e.g. Rosetta) – The most common terrestrial approach to drilling, this is also a common approach in space applications. However, many characteristics of conventional rotary drilling lead to high masses unfeasible for space missions, particularly at greater depths. However, this approach does have advantages, particularly in being able to cope with a large range of drilling strata. In addition, low mass rotary drills that minimize high mass elements (drill bit, drill string, high power motors) have been studied for space applications. Hill et al. [15] describes a rotating drilling system that, for instance, greatly reduces required axial forces, and hence the mass for a deep drilling system.
- Percussive (e.g. Beagle2 - PLUTO) – This method is generally efficient in power consumption and has been the optimum choice in several recent and proposed missions and studies. The method of producing percussive motion varies between designs, ranging from piezo-electric devices [16], roto-translational kinetic energy transfer [10]. Penetration rate is generally low, however, and subsequent transport of cuttings can also be problematic.
- Non-traditional – This includes use of laser, electron beams or microwaves etc. for drilling. These are generally limited by the high power requirements of current technology, but with improvements in both technology and drilling techniques this may become more attractive [17].

Potential future systems of particular interest, currently being designed, are described below:

- Ultrasonic/sonic frequency piezoelectrics actuators have been used in the prototyping of a drilling/coring device for use in space. The method has been shown to work on a variety of substrates, while requiring little external axial force, low system weight and low power [16].
- Two systems under development can be described as 'mole' devices, where a self-contained, relatively compact drilling device advances down the hole during drilling, with contact with the surface being provided by a tether for power and communication. SSX, in development for the detection of ice below the surface of Mars, will measure approximately 1 m in length and a few centimetres in diameter. Its power budget is relatively high at 200 W but its expected drilling depth of up to 5 km below the surface is the greatest of any of the concepts reviewed [10]. Notably, none of the systems listed in Table 1 were designed to drill deeper than a few metres [14, 10]. The Guided Mole Demonstrator (GMD) can also be described as a mole device but has significant design differences [18].

Auxiliary components such as cuttings removal and borehole imaging can also be important to a drilling system and are often affected by the choice of mechanism. For example, a wide borehole can allow easier access to instrumentation [19, 15] and conventional deep drilling often requires large amounts of extra equipment at the surface, especially for deep drilling.

Other idiosyncrasies of particular drilling devices have been found to be useful. The PLUTO mole device aboard Beagle2 for instance used its percussive drilling motion for locomotion across the surface as well as for drilling, giving limited mobility that made mobility for the whole lander unnecessary. Systems with synergistic functions such as this are one of the goals of biomimetic design. In conjunction with technologies such as MST it is hoped that more and more functions may be included in ever smaller packages, as they are in many biological systems.

Clearly, smaller size, lower mass, volume and power consumption are desirable wherever possible. Such improvements may be possible with microsystems, but the potential to fulfil other performance requirements and integrate other mission-required systems must be assessed in each case. On the other hand, with the many varied potential applications, and there being no definitive drilling solution, novel concepts have the potential to find a place in the field.

POTENTIAL FUTURE MISSION SCENARIOS FOR MICRO-DRILLING SYSTEMS IN SPACE

Miniaturised space systems call for miniaturised payloads, and hence micro-drilling systems. In addition, more ambitious payloads may call for the manipulation of micro-particles, requiring the use of miniaturised tools. This section describes some concepts for the application of micro-drilling systems.

Network of Miniaturized Modules

Space agencies, governmental organisations and industry are all involved in studying miniaturized, highly-integrated microsystems equipped with micro-sensors, and micro-actuators capable of communicating through optical or radio systems and able to scavenge energy from the environment (from vibration, radiation, chemical reactions at their interface with the environment, etc), as well as having some capacity for scientific payload. Smart Dust [26] and eCUBES [27] are two examples of such concepts.

Miniaturized drills could have an important role in sampling phases where individual soil granules must be investigated. Alternatively, or in addition, such probes might require anchoring on surfaces with low gravity or in hostile surface environments due to, for instance, atmospheric perturbations or seismic events.

Mole

Mole devices for subsurface exploration are increasingly considered as payload (Beagle2, SSX). Similar to the micro-penetrator concept, this consists of a small vehicle that moves its entire structure through the substrate as it drills. In previous and current applications this vehicle is connected to another on the surface through a tether for the supply of power etc. However, future systems could be envisaged where the mole is completely self contained.

In the case of a micro-mole, the micro-drill would be the principal system of the probe and, besides drilling, it could also provide any axial force required. Current mole-type solutions mainly use percussive drilling systems, though GMD [18] uses a rotating mechanism swell for non-coherent substrates. Clearly matching any biomimetic miniaturised solution to the relevant drilling substrate will be key in any future application.

In the case of a macro-mole, perhaps micro-drills might be used as energy efficient anchors, to provide required reaction force. Alternatively, aspects of drills inspired by small organisms may be found to be suitable for use in a macro-scale drill.

During the ESA funded study of biomimetics applied to space engineering [20, 21], a mission scenario for such a macro-drill utilising a biomimetic drill was designed (Fig. 1).

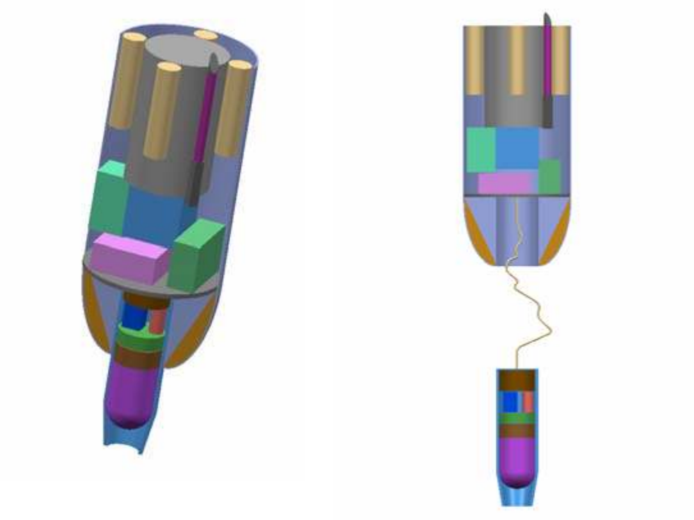

Fig. 1: Impacting probe for planet exploration

The penetrator can be envisaged with two main parts: a forebody, the penetrating part, and an afterbody, which remains on the surface. An umbilical cable connects the two parts. The aftbody is the cylindered terrabrake designed to arrest and absorb the impact in the surface materials of intermediate to high penetrability. As the forebody penetrates below the surface, the separable afterbody is left behind on the surface for communication purpose. The nose segment includes the drill and sampler subsystem used for scientific analyses of the soil.

Smart Grip

Micro-drills could be used to enhance adhesion or friction forces in various space applications, acting as a "dry adhesive" [28]. Micro active barbed needles could be integrated on locomotion system surfaces such as rovers' wheels, legged robots and climbing systems. This concept might even be extended to use in robotic end-effectors to enhance grip when rocks are gathered and handled. Stationary devices (such as landers, cameras or measurement systems) could also benefit from anchoring systems made from micro-drills, used to keep them in place on low gravity surfaces or challenging planetary environments (e.g. non-horizontal surfaces, high wind etc.)

Surface Measurements

Micro/nano drilling systems are also envisioned as auxiliary tools of payload designed to analyse extraterrestrial surface properties. The combined use of cantilever beams for atomic force measurements and devices able to make small holes in substrate could be a feature of future payloads for in-situ space research.

DRILLS IN NATURE

Two insect drilling systems were thought to be suitable for investigation. These systems, used by the female locust and a species of wood wasp named *Sirex noctilio* are, first of all, prime examples of drilling systems exhibited in nature at a much smaller scale than conventional man-made systems. With advances in MST, the interest in studying these systems is growing with the increasing possibilities to recreate their action at a comparable scale.

In addition, these systems stand out as unusual mechanisms, with characteristics and advantages not found in conventionally engineered systems. For example, one characteristic these systems share is their lack of need for the external supply of large axial forces for digging, a common requirement of conventional rotary drilling systems. Also, the fact that they do not sit easily in any of the drilling categories described in the previous sections, perhaps also suggests that these are unconventional solutions.

Locust Digging Mechanism

The ovipositor mechanism of the female locust was investigated. By stretching membranes between some of their abdominal segments, they are able to dig relatively deeply into the soil where they lay their eggs. This system can be seen on a real locust in figure Fig. 2.

Research has shown that it is the ovipositor valves that exert pulling forces needed for digging and extension of the abdomen, rather than a pushing mechanism such as increase of haemolymph pressure [25]. The following gives a basic description of the mechanism by which this system operates.

Fig. 3 shows a series of diagrams illustrating the mechanics of this system. Fig. 3 shows points of reference in this system. Frames 1-4 of Fig. 3 show the initial stage where the valves (left of point G) are thrust into the digging substrate. Note from the diagrams that this initial thrust is directed diagonally downwards, reaction force being provided from a bulging of the abdomen at the opposite side of the hole.

Next, the valves open (frames 5-9), both pulling the abdomen into the hole and clearing debris from the digging path. These tasks are separated between the valves, the lower ones being responsible for the pulling action, while the upper valves are used for clearing debris. As the system returns to its starting configuration, further down the hole, the length between points F and G decreases as the valves close, ensuring that there is a net movement of the system into the hole.

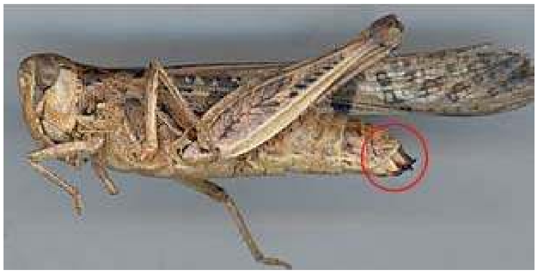

Fig. 2: Female locust with ovipositor valves highlighted (picture taken from www.enhg.org)

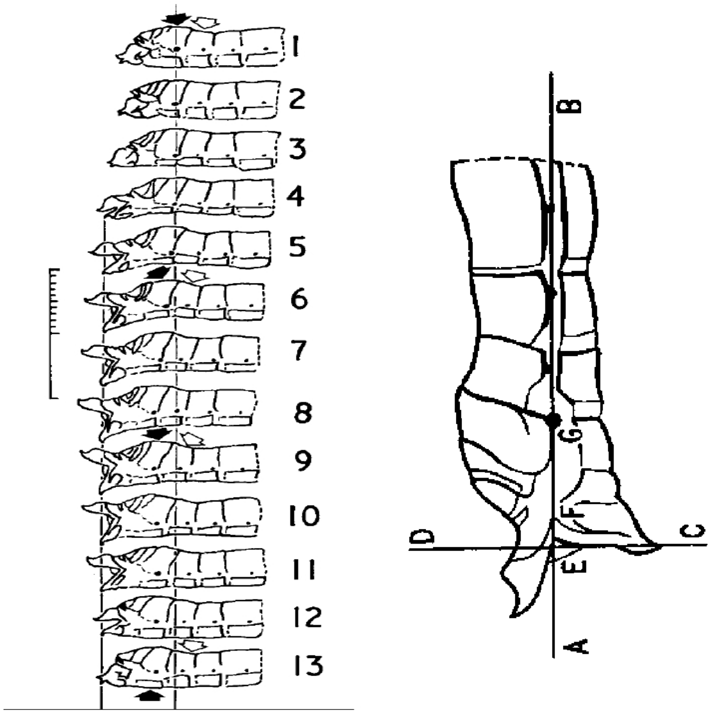

Fig. 3: Series of diagrams illustrating the locust ovipositor mechanics [25]

Wood Wasp Digging Mechanism

Another novel digging mechanism is displayed by *Sirex noctilio*, a kind of wood wasp [22]. In this case, the animal's ovipositor utilizes a reciprocal, longitudinal motion of a pair of valves while digging. While these valves slide against each other, backwards facing teeth on either valve are used to provide reaction force necessary to drive its partner valve into the wood since their design provides a highly directional resistance to the motion. A cyclical repetition of this process allows the mechanism to drill into the wood without the need for external reaction force. On different sides of the valves these teeth become pockets, shaped to enable debris to be transported away from the cutting edges and towards the surface rather than back down the hole. In addition to this clever design, the teeth are spaced to allow the forces due to digging to be spread evenly throughout the valves. Fig. 4 shows a model of ovipositor drill: the left valve pulls on a piece of wood cell while the right valve adds this to the compressive force, but is not limited by the critical Euler buckling load since the two valves of the drill stabilise each other like the outer and inner components of a Bowden cable. They can thus transmit tensile and compressive forces over a potentially infinite distance.

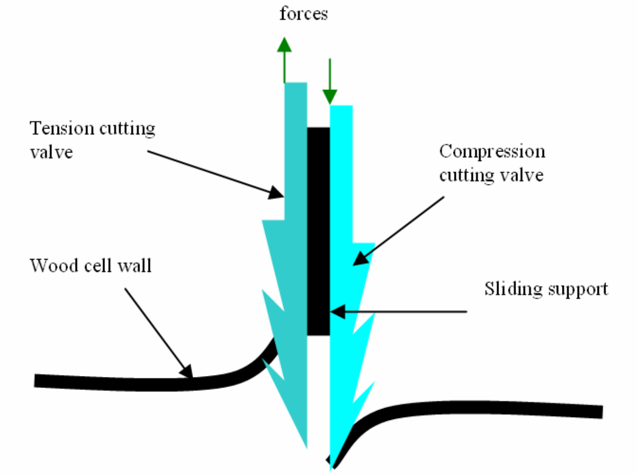

Fig. 4: Simplified model of ovipositor drill [22]

The drilling process begins when the wood wasp stabs its valves into the wood, to stabilise the mechanism. The first cut then uses the first few, proximally facing, "pull teeth" at the tip of its valves, one valve acting in tension and the other in compression. Drilling speed increases as the valves progress into the substrate and push teeth further up the drill can be used without fear of the assembly buckling buckling. All this is possible in a wood wasp mechanism around 0.26 mm in diameter and 10 mm in length. The wasp cuts at a rate of around 1 mm/min in the initial stage up to 1.5 mm/min at full speed. The capability of this drill is determined by the force required to drill through the substrate, the force able to be exerted by the teeth, and the bending strength of the teeth when engaged with the substrate.

ENGINEERING APPROACH AND DESIGN

The biological mechanisms described in the previous section have inspired both the concepts and engineering designs of two novel digging systems. The design took into account lessons learned from previous drills developed for use in space.

Locust Inspired Engineering Design

The locust ovipositor has been studied and analysed from different perspectives. Firstly, a simplified macroscopic physical model has been built in order to understand the dynamics of the locust ovipositor motion. Secondly, simulations of a two dimensional model has been performed considering different drilling substrates. Thirdly, possible manufacturing processes have been analysed and considered for a future three-dimensional micro-scale prototype.

Physical model

In order to have an engineering representation of the dynamics of locust ovipositor valves, a physical model was prototyped in plastic using rapid prototyping [30]. Fig. 5 shows the macro-scale physical model that was developed (scale 1:16).

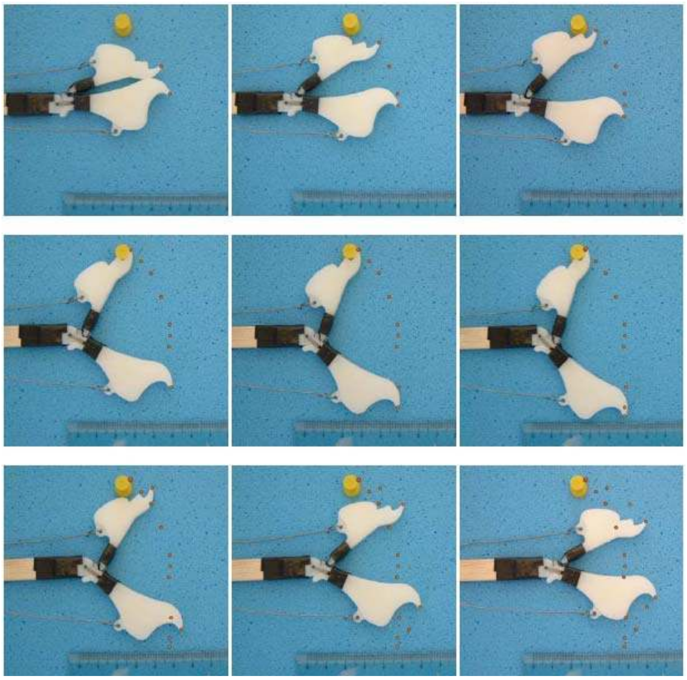

Fig. 5: Simulation of Locust inspired system by using a physical model with external contact

The smaller and larger valves are hinged to the apodeme tip, the connection having been achieved using metallic clamps. A wooden stick is used to simulate the apodeme of the locust and two wires operate the two valves, simulating the action of the muscles and tendons. Operating the muscles by simultaneously pulling the two extremities of the artificial muscle, the motion shown in Fig. 5 is achieved.

Simulated model

The locust ovipositor apparatus was also mathematically modelled in order to assess the performance of an engineered locust excavator. The natural digging system works on coarse granular soil, and is based on displacement of the soil particles. The motion executed by such a system consists of a mixture of penetration of the digging apparatus into the soil, cutting of soil, and scooping the soil particles towards the wall of the hole.

One of the most important elements in an earthmoving process is the medium. The medium can be classified on the basis of a number of characteristics or functional definitions, and can conveniently be described as clay, particulate, soil, or a combination of the previous. Clay is a finely grained earthy material that exhibits cohesion and plasticity. Particulate is a coarse-grained material, often assumed to be cohesionless and without adhesion. Soil is a mixture of loose sediments (clay, sand, silt, etc.) with consistency determined by water content and mixture ratio.

Physical properties such as density, friction, cohesion, and adhesion characterize a medium. Density plays a major role in tool-medium interaction since it defines the weight of the material being moved. Friction is often an influential parameter in cutting or penetrating a medium and internal friction is considered to be an inherent characteristic of the medium. In the specific case of a granular medium, the shear resistance is due to friction, rolling and interlocking of particles. External friction between soil and the surface of the digging tool depends largely on tool surface roughness. Cohesion can be thought of as the strength of the soil, which does not depend on the applied force. Adhesion is the tension force required at the mutual contact surface of two rigid bodies to separate them. Adhesion of soil to tilling tools causes a normal force on the contact surface and increases the frictional force.

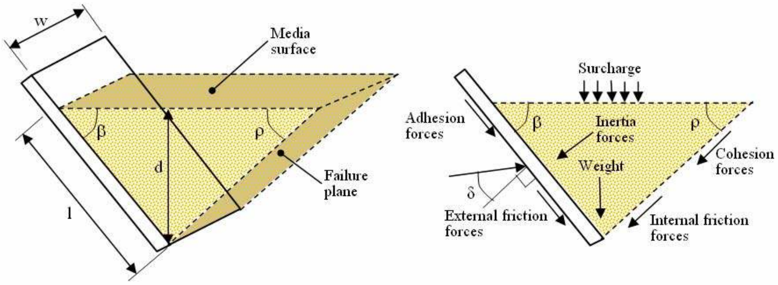

Fig. 6: Soil-tool interaction mechanism and main parameters

Modelling of the digging mechanism involves the assumption of a failure mechanism of the medium. The magnitude of the force required to cause the failure is a function of the shear strength of the medium and the dimension of the internal rupture surface. In our simulation the medium is homogeneous, which implies that any property is assumed to be constant, characterised by a continuous and isotropic behaviour. Mathematical modelling of the excavation process can enable the design of an excavator tool based on the mechanism under study and to determine the required power. The force required for the excavation is calculated on the basis of the model formulated by Reece [23 and 24]:

Eq. 1 $$F = \left(\gamma g d^2 N_\gamma + c d N_c + q d N_q\right) w$$

where F is the resistive force experienced by a digging tool, γ is the soil density, g is the gravity, d is the tool depth below the soil, c is the soil cohesion, q is the surcharge pressure acting vertically on the soil surface, w is the tool width, and N_γ, N_c, and N_q are dimensionless coefficients due to soil density, cohesion and adhesion properties, respectively. The parameters governing the soil-tool interaction mechanism are depicted in the following Fig. 6.

Various soils have been considered in order to calculate the resistive force of a mechanism based on the locust digging apparatus. The soil parameters and the values of the forces required to fail the soil are reported in Table 2. The cases considered comprise the lunar soil [24], three types of granular soil (loose sand, medium density sand and dense sand), and two types of cohesive soil (sandy clay).

Table 2: Soil parameters and values of resistive forces calculated using the Reece model

Soil properties	**Unit**	**Lunar soil(1)**	**Loose sand**	**Medium density sand**	**Dense sand**	**Sandy clay 1**	**Sandy clay 2**
Soil density	kg/m^3	1960	1700	1800	2000	1950	1950
Soil cohesion	Pa	9,00E-06	0	0	0	10000	20000
Angle of soil-soil friction (ϕ)	deg	37	30	37,5	45	28	40
Angle of friction between soil and blade (δ)	deg	24	24	24	24	24	24
Tool depth below the soil	m	0,01	0,01	0,01	0,01	0,01	0,01
Tool width	m	0,005	0,005	0,005	0,005	0,005	0,005
Rupture angle (β)	deg	30	30	30	30	30	30
Tool angle (ρ)	deg	60	60	60	60	60	60
Gravity	m/sec^2	9,81	9,81	9,81	9,81	9,81	9,81
Surcharge pressure	Pa	0	0	0	0	0	0
Nγ		2,192	1,701	2,236	3,112	1,591	2,475
Nc		3,295	2,947	3,325	3,946	2,868	3,495
Nq		4,385	3,403	4,471	6,225	3,181	4,950
Resistive Force experienced at the blade tip	N	2,12 E-02	1,42 E-02	1,97 E-02	3,05 E-02	1,45	3,52

(1) Willman and Boles, 1995

A numerical model has been developed in order to simulate the digging mechanism of the locust ovipositor mechanism. The model was built using DADS, a code for the multi-body analyses. The schematic of the model, which had approximately the same dimensions as a real locust ovipositor, is shown in Fig. 7. The upper valve (in blue in Fig. 7) is modelled as a 3mm long prismatic element. It is connected to the lower valve (in red) through a revolute joint (see also Fig. 5 for a comparison with the physical model). The lower valve is connected to the apodeme through a revolute joint. The definition of a prismatic joint between the apodeme and the ground allows the translation of the system in horizontal direction. The simulations, which were performed, are based on the assumption that the system is working in a vertical configuration inside a hole. The sides of the hole are represented by the yellow circle in Fig. 7.

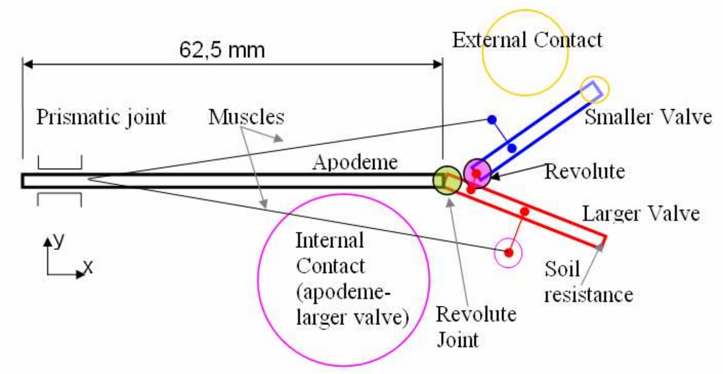

Fig. 7: Scheme of the multi-body model of locust ovipositor

The smaller valve has some freedom to move inside the hole before reaching the side wall. This is due to the size of this valve and to the angled initial configuration of the valves with respect to the hole. In fact, when the valves are closed, the line connecting the contact point of the tips of the valves with their common hinge lays at an angle of about 20 degrees with the respect to the axial direction of the apodeme (see Fig. 3).

The larger valve is instead always in contact with the soil to be swept away. The force between the soil and the larger valve is modelled using Eq. 1. Motion of the larger valve is limited by the apodeme encumbrance which is represented by the pink circle in Fig. 7. Two muscles connect the apodeme to the two valves.

The mechanism's action can be described in two phases. In the first phase, the valves are pulled by the muscles. The smaller valve pushes against the side of the hole to allow the larger valve to sweep soil away from the front of the mechanism. The larger valve moves until in contact with the apodeme. In the second phase, the smaller valves continues to push against the side of the hole and causes the whole apparatus to move forward in the empty space created during the first phase.

The results of the simulations performed predict values of force at the tip of the lower valve in the range of 0.0142÷0.0305 N for granular soils, and 1.45÷3.52 N for cohesive soils.

A bio-inspired locust digging mechanism, which has muscles able to exert a maximum force of about 0.45 N (value computed by considering the cross section of the muscle of the natural locust ovipositor), seems to not be suitable for digging through cohesive soils, where the force required to cause failure of the soil is higher than for granular soil.

The model predicts a movement of about 1 millimetre per cycle of opening and closing of the valves when “medium density sand" composition is considered (see Table 2) and when the muscles exert 10% of their maximum force (45mN). Such a prediction agrees with experimental observations of the natural locust ovipositor [25].

Manufacturing processes

Several micro-fabrication techniques can be considered for the production of a planar micro drill. However, the production of a 3D analogue should be the focus. The model of the replica locust valves is shown in Fig. 8. The shape of the biological system has been reproduced in order to assess possible engineering issues that could occur during the manufacturing phase. Industrial processes that could be imploded to build such a micro-system include EFAB [1], LIGA [4], FIB [5] and WEDG [6]. The technological difficulties in the construction of the rigid mechanical valves shown in Fig. 8 lie in its three dimensional structure, concave shapes and the dimensions of the valves, which range from sub-micro to millimeter scales. A feasibility analysis of the processes needed to build the locust inspired digging mechanism is necessary and will be a further step in assessing the performance of the system, primarily in terms of reliability, mechanical strength, accuracy and cost.

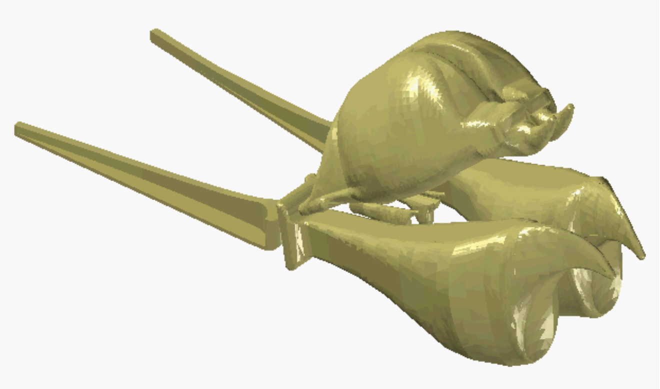

Fig. 8: Three dimensional model of the locust digging valves [30]

Wasp Inspired Engineering Design

Several technologies could be considered to manufacture the reciprocating drill inspired by the wood wasp. Here we discuss two solutions that have been envisioned.

The first process, that we called "vertical design", concerns a stack of wafers bonded together from individually engineered parts. The second one, which is a "planar design", is obtained from a single wafer and has sub-design possibilities for models with increasing complexity.

Fig. 9 shows the vertical design process. The first step (Fig. 9.A) is the use of photolithography performed using a positive resist (e.g. S1813). A square pattern is formed on a silicon wafer with a thermally-grown layer of SiO_2. Then, the SiO_2 is etched in a buffer HF solution and the resist is stripped off with acetone (Fig. 9.B). The exposed silicon is isotropically etched in KOH (to create 10-µm-wide teeth) and the remaining SiO_2 is removed in a HF solution (Fig. 9.C). The following step again concerns the use of photolithography with a thick (> 15 µm) positive resist (e.g. SJR 5740 from Shipley) as shown in Fig. 9.D. Then, the exposed Si is anisotropically etched in a deep reactive ion etcher (over a height of about 14.14 µm) and the SJR 5740 is stripped off with acetone (Fig. 9.E). This process is repeated with several wafers of different thicknesses and different pattern dimensions (Fig. 9.F) that are successively bonded together and cut to mimic the animal valve. Fig. 10 shows the final three-dimensional shape.

With regard to the "planar design", there are several possibilities using micro-manufacturing to obtain the same final design shown in Fig. 11. Three possible solutions are proposed here.

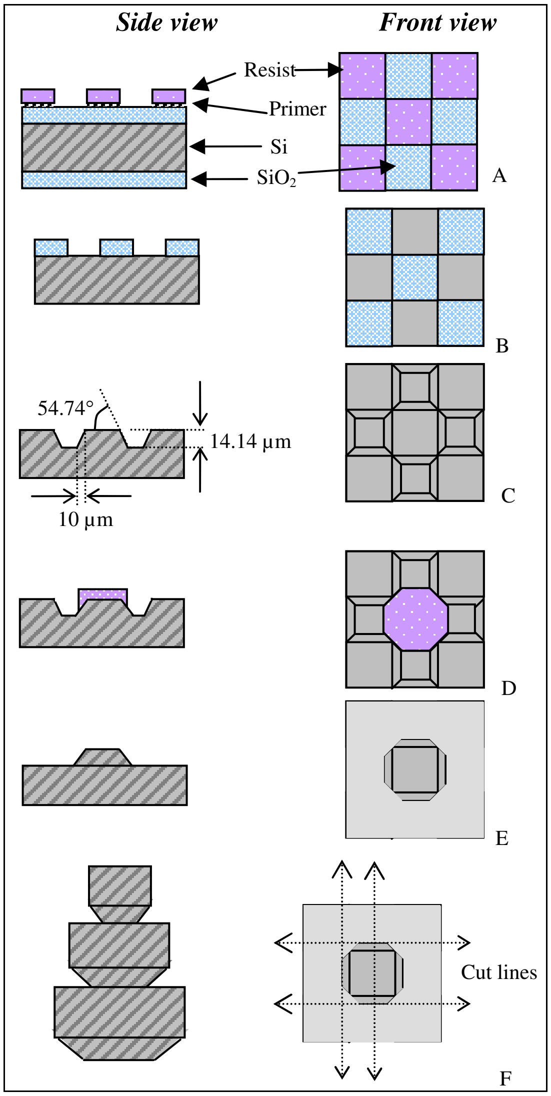

Fig. 9: Vertical design process

In the first case, the structural material (e.g. polysilicon) is deposited on a layer of sacrificial material, then the valve outline is patterned with photolithography (e.g. with S1818) so that the valve can be etched with a deep reactive ion etcher. The resist is then stripped off, as well as the spacer layer. In this way the valve can be released from the wafer surface.

For the second solution, a thick positive resist (e.g. multilayers of SJR 5740) is used as a mould for the structural material. The release of the structure could simply be done by stripping off the mould in acetone.

Thirdly, a LIGA process [4] is considered. A sacrificial layer of titanium is first deposited onto the wafer. The mould is then created with AZ4562 and the valve is formed by nickel electroplating within this mould. Then, the resist and the titanium are lifted off so that the valve can be released from the wafer surface.

The planar design can undergo some variations adding some complexity and leading to a better bio-inspired digging system (see Fig. 12). A multilayer mould, obtained using certain procedures previously described, should comprise several layers (totalling 50 µm) as shown in Fig. 13.A. After the structural material has been deposited (see Fig. 13.B), the desired shape is patterned with photolithography, then the exposed structural material is etched with a DRIE as in Fig. 13.C, and the resist mask is stripped off. A second photolithographic step creates a second pattern, where the exposed structural material is etched again (Fig. 13.D) and this process is repeated. Using this strategy, smaller and larger part of the valve can be shaped (Fig. 13.E).

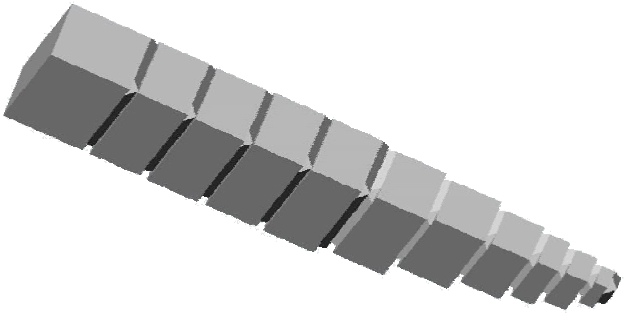

Fig. 10: Valve made with the vertical design (the wafer thicknesses vary from 50 to 150 µm)

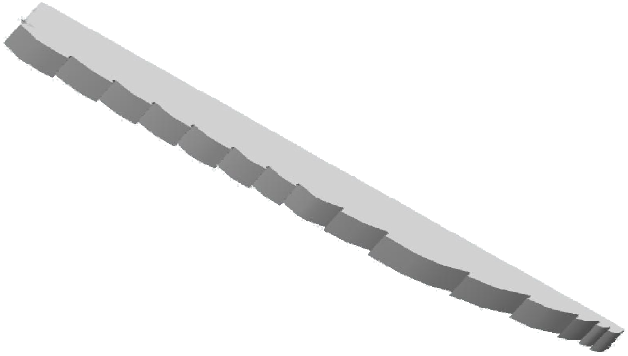

Fig. 11: Valve made with the basic planar design (the structural material is either Ni or polysilicon, depending on the process)

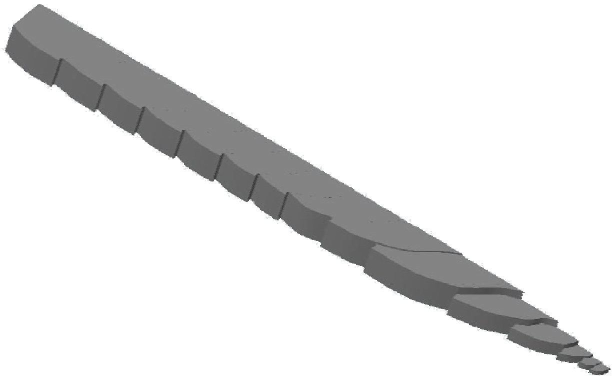

Fig. 12: Valve made with the second variation of the planar design

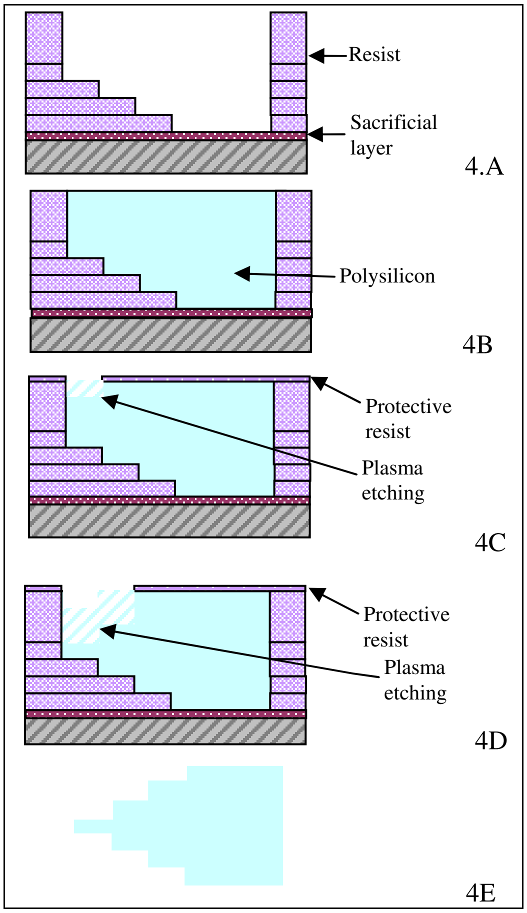

Fig. 13: Second variation of the planar design process

Macro-Scale Preliminary Tests

In order to verify the feasibility of a micro-drill based on a reciprocating motion, a macro scale digging mechanism has been designed and built. The simplicity of the manufacturing phase, availability of off-the-shelf actuators able to impose an alternating motion and the low cost made this a convenient preliminary assessment.

In this experiment, the drill bit was manufactured from metal, to withstand tests in hard substrates. We used off-the-shelf coach screws with a suitable diameter, machined to be adjusted to the actuation unit. The resulting drill bit is shown in Fig. 14. Tests were performed in three different condensed chalk, lime mortar and non-fired clay (see Table 3). A range of voltage of 0-9 V and a power input of 0-10 W was used and holes with 18 mm diameter were dug at a cutting speed of 0-0.38 m/s. Results show that harder material like clay takes longer to drill into than softer materials such as mortar and chalk.

Fig. 15-17 show drilling time versus drilling depth at different input powers and for the three different substrates [29]. Experimental data (coloured dots in Fig. 15-17) show that the drilling speed increases as the drill digs deeper. This is probably caused by the formation of cracks in the substrates while the drill is advancing. Despite this effect, Fig. 15-17 also show linear extrapolation of the data which can be considered as a worst case prediction useful for a system design. The slope of the lines indicates the approximated drilling speed, which increases as the input power increases.

It should be noted that this drilling system is inherently suitable for percussive motions. In particular, when the reciprocating motion is controlled at high frequencies, the two valves cyclically impact on the substrate increasing the effectiveness of the digging process.

Fig. 14: Metal drill bit [29]

Table 3: Physical properties of tested substrates

Substrates	Density (kg/m^3)	Compressive strength (MPa)
Condensed chalk	1500	0.65
Lime mortar	1560	0.95
None-fired clay	1769	4.8

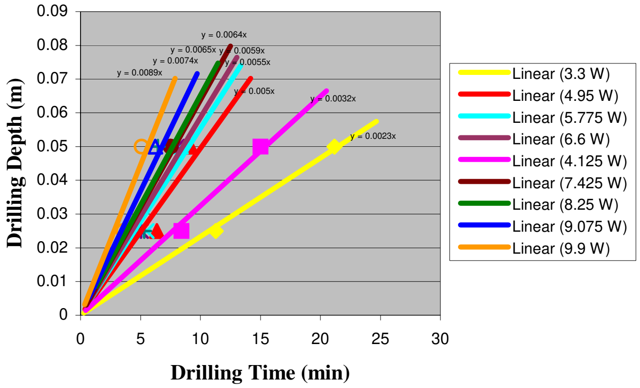

Fig. 15: Drilling time versus drilling depth for clay [29]

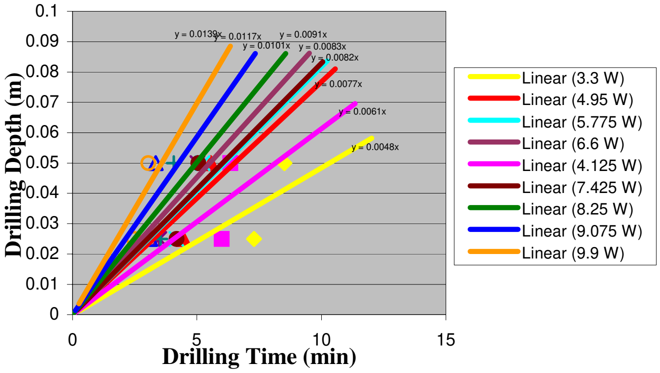

Fig. 16: Drilling time versus drilling depth for mortar [29]

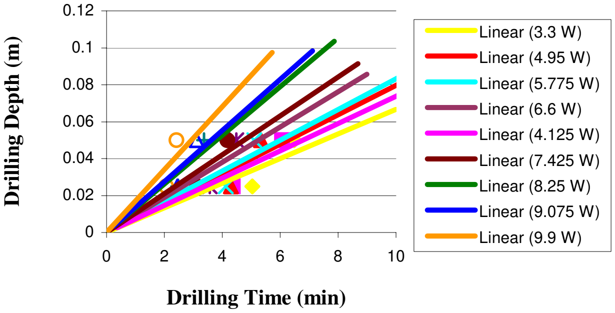

Fig. 17: Drilling time versus drilling depth for chalk [29]

FUTURE WORK

In the framework of this study, a biomimetic approach has been followed in the engineering design of micro-drillers for space applications. Further research is needed to realise the concept designs proposed. A breadboard phase of a miniaturised prototype is needed in order to assess the practical feasibility of the concepts. In order to perform tests at micro-scale, the design of the actuation subsystem is fundamental. Possible candidate actuators can be based on piezoelectric materials, electrostatic motors, electro-active-polymer materials, shape memory alloys and other miniaturized motors. Linear actuators could perhaps represent the best choice from a bio-inspired point of view and probably also from a technological point of view. However a comprehensive study is needed to make an optimal choice. The integration of the micro-drills with the actuation subsystems would enable a test campaign, necessary to assess the realistic performance of the drills and the effectiveness of the proposed drilling techniques for different drilling strata, scales and functions, and also to compare the proposed drills with their natural counterparts.

CONCLUSIONS

Various aspects of the design of, and motivation for, micro-drilling systems for space applications have been presented. The most interesting outcome of the research performed is perhaps the demonstration of combining Micro Systems Technology and biomimetics to synergistically conceive new engineering systems for space applications. This paper shows and emphasises the bio-inspired approach that has been pursued presenting two novel solutions for micro-drilling mechanisms. The first, inspired by the female locust ovipositor digging system, has good potential for digging substrate having granular form. Three dimensional models and preliminary planar simulations show positive results for the systems proposed. The second concept design was inspired by the wood wasp ovipositor mechanism. Preliminary analysis has been performed on this system, and engineering models have been proposed, considering constraints imposed by micromachining processes. The macro-scale test that was performed showed promising results, although tests at micro-scale will be needed to assess the scalability of the design for future space missions.

Potential applications in space have been proposed, mostly in the area of extraterrestrial drilling or sampling. Any interest in these miniaturised systems for space applications will probable come from the major space agencies with interest in extraterrestrial science, or from their industry contractors.

However, in the further study and development, other applications may emerge, using the principles of these biological systems in different ways. Given the strengths of the organisms, the possibility that attractive engineered systems may be derived for terrestrial applications, or at macro scale, should not be ignored.

Current and past state of the art in space drilling and sampling has been reviewed, with the conclusion that for appropriate mission architectures and objectives, Biomimetic drills such as these may be attractive options. This is, of course, also dependent on a number of other factors, including continued interest in extraterrestrial drilling and sampling. Furthermore, work in the design of miniaturised systems for space applications is at a very early stage, the emergence of these particular systems as optimal choices is far from certain, and the use of these systems in space will not occur in the near future.

Aside from the stringent requirements placed on space hardware, the designs themselves are still at an early stage. In addition to the near future work described in the previous section, any thought of practical application will require further investigations including: 1) thorough simulations to study in detail the working of the device in a range of different environmental conditions; 2) integration with other systems e.g. science payload, power etc.; 3) study of materials and manufacture, especially for extraterrestrial use.

Development costs for individual micro-scale devices will probably not be deemed worthwhile specifically for space use. Use of such systems will probably be highly dependent on several factors including: 1) development of micro and nano technologies for space use; 2) development of missions where small sampling or drilling capability is required; 3) low cost spin-in from terrestrial applications.

While the eventual cost of developing and implementing such a system is highly uncertain, it is clear that the biggest potential benefit in terms of cost is in allowing drilling or sampling in space at reduced mass and volume.

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