UTOPUS TRACTION TECHNOLOGY: A NEW METHOD FOR PLANETARY EXPLORATION OF STEEP AND DIFFICULT TERRAIN

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Abstract
After several successful missions to explore the surface of Mars with wheel-based rovers, the exploration of difficult and steep terrain has gained prominence in the field of planetary exploration, calling for new methods of vehicle locomotion which offer stability in steep and difficult terrain. UTOPUS traction technology offers a new method of locomotion which abandons the wheel paradigm for a two-phased anchoring and de-anchoring technique by driving removable crampons into the ground. In agriculture it minimizes soil compaction, reduces energy consumption, and produces a draft force similar to much heavier wheel-based tractors.

Here we investigate whether the inherent stability of locomotion based on removable crampons allows exploration of steep and difficult terrain. We present experimental results from climbing and descending a mound of heterogeneous dust, sand, and granular material at the critical angle of repose, at an inclination of 25–40 degrees. The UTOPUS vehicle repeatedly climbed and descended the mound safely. An initial problem when reaching the top of the mound was solved by rebalancing the vehicle. Occasional failure occurred when the vehicle had strong lateral inclination, or on patches of very loose ground, suggesting the need for some design changes to the current model.

Keywords: crampon-based traction, inching locomotion, push-pull locomotion, planetary exploration, steep terrain exploration

1. Introduction

In recent years the exploration of difficult and steep terrain has gained prominence in planetary exploration. The observation of recurring slope lineae (RSL), which might indicate the presence of water on Mars, has spurred particular interest in the exploration of steep slopes. RSL may be found on bedrock, slopes with fine-grained soils that are slowly permeable, and slopes covered by permeable materials such as windblown sand (supplement of McEwen et al., 2011). Another interesting feature to be explored are the craters formed by meteorite impacts which expose the deeper soil layers.

Vehicle exploration of RSL and craters requires safe navigation of slopes which are covered in regolith, which is a heterogeneous layer of dust, gravel, and broken rock. The slopes can have a relatively steep inclination of 25–40 degrees and can be close to the critical angle of repose. The low gravity which characterizes lunar exploration in particular might pose an additional problem, resulting in very low soil density. A vehicle which moves on such slopes is in danger of sliding down, rolling over, or being buried by an avalanche. The uneven terrain and the danger of uncontrolled motion can also result in the vehicle being stuck between rocks or on soil which is too soft and too loose to generate any traction by wheel.

Seeni et al. (2008) provide a general discussion of mobility concepts for planetary surface exploration. Inching locomotion for exploration in difficult terrain has been discussed by Wettergreen et al. (2010), Moreland et al. (2011) and Creager et al. (2012). The idea of inching locomotion itself goes back to at least Schreiner and Czako (1973). Most versions of inching locomotion use wheeled vehicles and keep one pair of wheels static while the other pair of wheels moves. Some versions use additional stabilizers. Moreland et al. (2011) find that static wheels provide about twice as much tractive force as rolling wheels.

The draft force of a rod or tine in the ground has been discussed in depth by Hettiaratchi et al. (1966), Hettiaratchi and Reece (1974) and Godwin and Spoor (1977). Godwin and Wheeler (1996) study soil penetration and maximum sustainable pull of a broad land anchor and find that models based on the equations of Hettiaratchi et al. and Godwin and Spoor agree with the measurements. Draft forces in extraterrestrial regolith are discussed for example by Wilkinson and

DeGennaro (2011), King et al. (2011) and Vrettos (2012). Ziglar et al. (2008) and Kohanbash et al. (2014) explore the advantage of driving a circular rod vertically into the ground to exploit the subsurface soil strength in order to provide additional stability during turning maneuvers on a slope, and to create a braking force during descent. To the best of our knowledge, the idea to insert narrow retractable rods or tines into the ground in order to push or pull a vehicle forward by inching locomotion has not previously been studied.

The UTOPUS traction technology (Bover, 2011; Nannen et al., 2016) uses inching locomotion to push-pull a vehicle forward from retractable rods or tines which it drives into the ground to exploit the subsurface soil strength. We use the term "crampon" to distinguish a rod or tine which is used to generate traction or pull from other soil-engaging rods or tines. This crampon-based traction technology has originally been developed to minimize soil compaction and to decrease the energy consumption of an agricultural cultivator to the point where solar powered field operation becomes feasible. Due to slip and tire flexing, wheels are energetically inefficient on soft agricultural soil. They need heavy ballast to generate traction, which compacts the soil and reduces soil fertility. As will be explained in detail in the following chapter, UTOPUS replaces the ballasted wheel by the inching locomotion of two alternating frames with crampons which are driven into the soil at regular intervals to exploit the subsurface soil strength for traction. The resulting locomotion allows a lightweight vehicle to generate a tractive force which is normally associated with a much heavier tractor, and at a better fuel economy. As the crampons prevent slip, provide lateral stability, and allow solar powered operation, the question arises whether this traction technology is appropriate for the exploration of extraterrestrial slopes. The present article offers a first examination of this question.

Terramechanical research on soil behavior and vehicle traction in gravities different from Earth's gravity of 1 g has been conducted for several decades, primarily for gravities which are significantly lower than 1 g. Gravity on Mars is about 0.38 g, and gravity on the Moon is about 0.16 g. Soil properties which affect bearing capacity and traction, especially a type of traction which relies on subsurface soil strength, include shear strength and soil density. The value of these properties at a given depth depends on the weight of the soil column above it, which causes the soil particles to be packed tighter and to interlock. As the weight of the soil column decreases with decreasing gravity, the tractive properties of regolith can be expected to change significantly in low gravity.

Efforts to understand the effect of low gravity on the tractive properties of soil include the use of soil simulants with a low specific weight which replicate extraterrestrial soil conditions on earth (Li et al., 2012, Zou et al., 2015), laboratory setups which reduce the effect of gravity e.g. by inclining the surface and all devices acting thereon (Zou et al., 2015), or by conducting experiments in planes during parabolic flight maneuvers which achieve a temporary low gravity (Kobayashi, 2010, Nakashima 2011). Moreland et al. (2014) introduce soil optical flow technique to study soil behavior under a vehicle. While not specifically addressing gravity, the method promises relevant insight also for the present innovation. Numerical methods like the Discrete Element Method (Smith et al, 2014, Moreland, 2013) provide computational tools to calculate the behavior of regolith under different physical conditions. These tools are useful to design for example the optimal lug height and thickness of a lugged wheel on flat terrain. Whether the existing methods can predict the behavior of a vehicle in low gravity on a slope at the angle of repose has yet to be tested.

For the present investigation we rely on the simple method to pile regolith to mounds of 3 to 4 meters and to let it settle for several months, such that the material has settled at the natural angle of repose. It will have to be understood that the resulting material has a higher density, a higher shear strength, and a higher subsurface strength than what can be expected on the Moon and on Mars.

The remainder of the article is structured as follows: Section 2 formally describes the UTOPUS traction mechanism. Section 3 presents the experimental setup. An evaluation of the experiments follows in Section 4. Section 5 concludes.

2. Traction by retractable crampons

The UTOPUS mechanism uses retractable anchors or crampons to generate traction. The crampons are placed at the back of at least two frames, which are placed one in front of the other, and which are interconnected by a push-pull mechanism, resulting in what is known as inching locomotion (Moreland et al., 2011). Soil strength increases with depth. Wheels or tracks generate traction through a combination of surface friction (through their surface contact area and their lugged profile) and subsurface strength (by using ballast which compacts and interlocks the particles under the tire and which directs the force vector of the tire downwards such that deeper soil layers participate in the tire-soil dynamics). The amount of pull which can be generated with a wheel or track depends principally on the weight applied to it (Wismer and Luth, 1973; Zoz and Grisso, 2003). Crampons rely on subsurface strength. The amount of pull which can be generated with a narrow vertical tine depends principally on its depth in the ground (Hettiaratchi et al., 1966; Hettiaratchi and Reece, 1974).

A crampon needs to be driven into the ground with force. In order to avoid additional actuators, the current UTOPUS design attaches the crampons to the back of their respective frames with a horizontal hinge and crampons are shaped such that any backward pressure will drive the crampons into the soil in a circular motion, see Figure 1, 2 and 5.

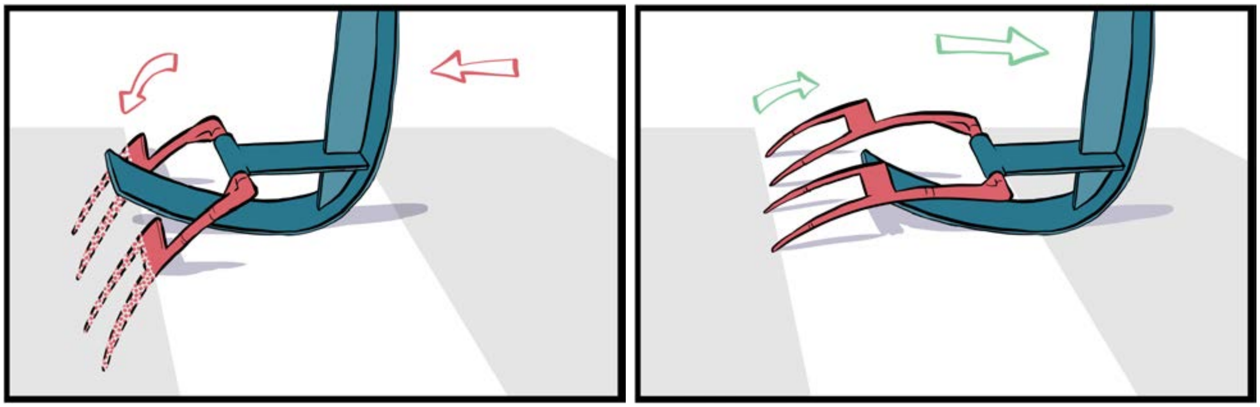

Fig. 1. *The crampons are actuated by the motion of their respective frames.* ***Left****: When a frame is pushed backwards (in this illustration: to the left), its crampons are pushed into the ground in a circular motion.* ***Right****: When a frame is pulled forward (in this illustration: to the right), its crampons are pulled out of the ground and slide over the ground.*

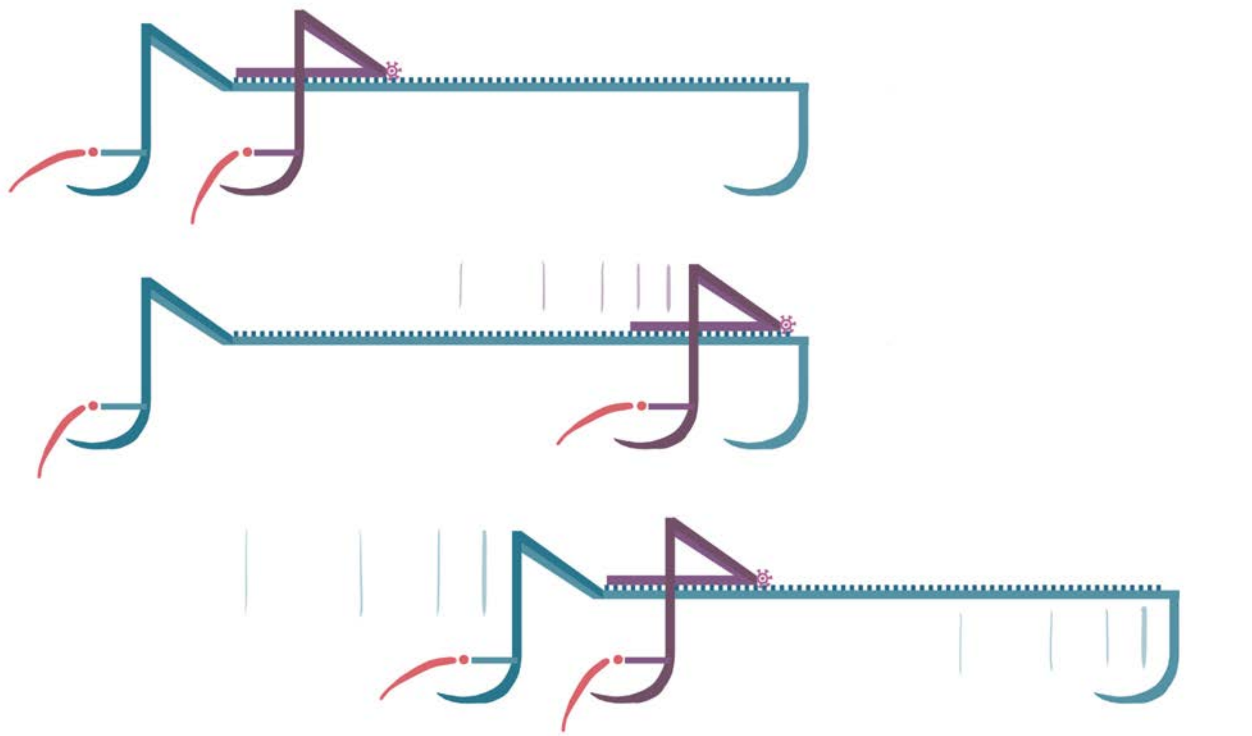

Fig. 2. *The push phase of the UTOPUS motion cycle in lateral view. The vehicle moves from left to right. Note the two crampons in red attached to the back frame and the front frame (in purple). Note also that the shaft has an additional element in front of the purple frame for balance. This additional element has no effect on the traction mechanism.* ***Top:*** *At the end of a pull phase the front crampon is still anchored in the ground while the rear crampon is sliding over the ground.* ***Middle:*** *UTOPUS pushes the two frames apart. The front crampon has been pulled out of the ground and slides over the ground while its frame advances. The rear crampon has been pushed into the soil, firmly anchoring its respective frame.* ***Bottom:*** *UTOPUS pulls the two frames together again. The front crampon has anchored itself firmly in the ground. The rear crampon has been pulled out of the ground while its frame advances.*

Fig. 3. *An agricultural version of UTOPUS cultivating an onion field with energy autarky. In the images the vehicle moves from bottom left to upper right. L**eft:** During the pull phase the back frame (left) advances while the crampons of the front frame (right) have been driven into the ground and provide traction. **Right:** At the start of the push phase the crampons of the back frame are driven into the ground, allowing the front frame to advance.*

In the present configuration the two frames of UTOPUS are connected by a long shaft, see Figure 2. A motion cycle of UTOPUS consists of a pull and a push phase, which can be described as follows: assume that the connecting shaft is fully extended and that the crampons of the front frame are anchored in the soil. As the vehicle starts to contract the shaft, the front frame is held static by its crampons while the rear frame is pulled forward. The crampons of the rear frame are pulled out of the ground and slide over the ground. This is the pull phase. When the shaft is fully contracted, it will start to extend again. At this point the crampons of the rear frame are pushed back into the soil, holding firm, while the crampons of the front frame are pulled out of the ground and slide over the ground while the front frame is pushed forward. This the push phase. Because a crampon needs to be driven into the ground only once for every pull and push phase, its tractive efficiency can be significantly better than that of any wheel-based device.

The original design goal of the UTOPUS traction mechanism was a device for agricultural cultivation which would not degrade soil and which would have such a low energy consumption that solar powered operation would become feasible, see Figure 3. Because crampons can generate pull with much less weight than a tractor, they can be expected to minimize soil compaction, preserve soil structure, increase rain water infiltration, and increase soil fertility. The resulting agricultural device has been described by Bover et al. (2016). As the crampons offer good traction, stability, and fuel economy, the UTOPUS traction mechanism might offer an alternative to wheel-based rovers for planetary exploration missions.

As already pointed out, there are two movable frames which determine the UTOPUS motion cycle. The frames are connected by an extensible shaft. The length d by which this shaft extends and contracts is a principal factor in the calculation of the resulting motion. During the pull phase the back frame advances by a distance d towards the front frame and during the push phase the front frame moves a distance d ahead of the back frame. The shaft in Figure 3 consists of a metal bar to which a chain is welded. The front frame is also welded to the shaft. The back frame moves along the shaft by a system of small wheels and guides. An asynchronous electrical motor with a cogged wheel is mounted on the back frame such that the cogged wheel interlocks with the chain on the shaft. The motor needs a fixed number of rotations to extend and contract the shaft. Let t be the duration of a single pull or push phase when the motor is driven at nominal frequency and load. We find that the upper bound for the velocity v of UTOPUS is

$$v = \frac{d}{2\,t}.$$

The real velocity is usually somewhat lower because it takes time ts for the variable frequency drive to switch the rotational direction of the motor, and because the crampons tend to slip a certain distance backwards through the ground when they are driven into the ground: at the beginning of a push phase the back frame B slides backwards by a distance db while the back crampons penetrate the ground. Likewise, at the beginning of a pull phase the front frame F slips backwards by a distance df while the front crampons penetrate the ground. While the switching time ts depends on the control settings of the variable frequency drive and is the same for a pull and a push phase, the slip distances *db* and *df* depend on local soil conditions and are highly variable. The effective velocity *ev* can be calculated as

$$ev = \frac{d - (db + df)}{2\,t + \,2\,ts}.$$

Figure 4 illustrates the resulting motion dynamics of UTOPUS. See Table 1 for an example of some real world measurements of slip and speed. In order for UTOPUS to have a useful velocity, the slip distances *db* and *df* and the switching time *ts* should be minimized.

Due to its peculiar traction mechanism, UTOPUS has several crampons anchored in the ground at all times. This specific property promises to be of advantage when navigating steep terrain of loose regolith, and might help prevent the vehicle from sliding down and rolling over. However, the inching locomotion as currently implemented might also pose a few challenges when navigating difficult terrain. Push-pull locomotion can be realized in different ways, the most straightforward and easiest to implement being an extensible shaft which forms an otherwise rigid connection between the two frames. Such a rigid connection poses no difficulties on flat terrain without obstacles, but might be problematic in rough terrain with little depressions, pits, boulders and ridges which the vehicle needs to pass. When passing a depression, the distance between shaft and ground increases, which might reduce the depth of the crampons in the ground. When passing a ridge, the shaft will scratch over protruding boulders and ridges, possibly interfering with the drive system. The axis of advance will also often not be horizontal, such that the shaft will at times push the front frame into the ground in front of UTOPUS, and at times into the air.

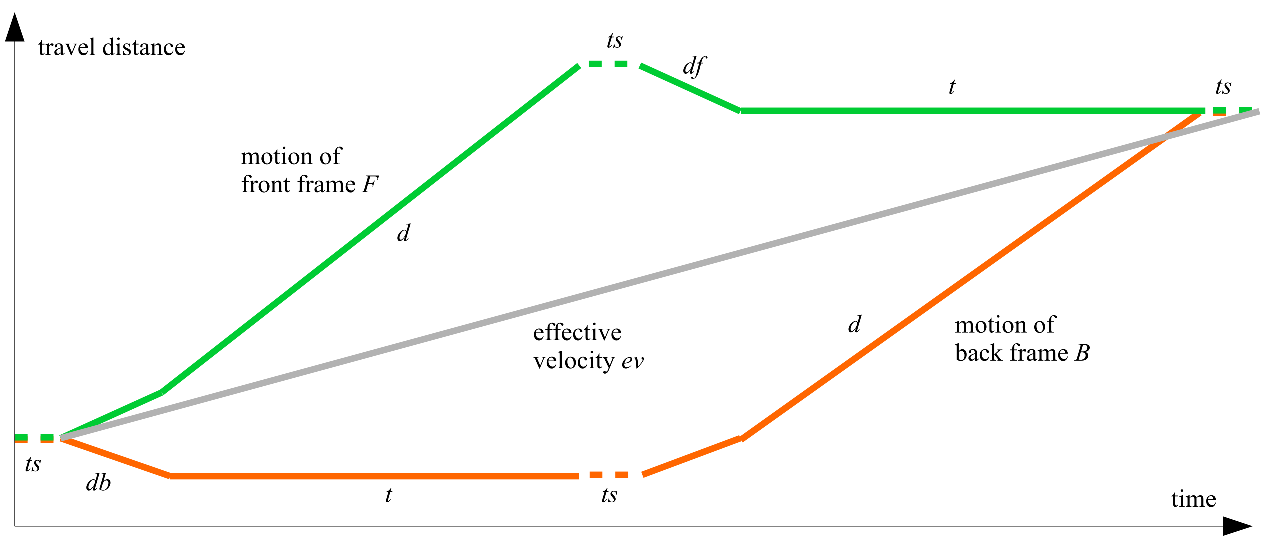

Fig. 4. *Diagram of the motion dynamics of UTOPUS. The orange line illustrates the motion of back frame B and the green line illustrates the motion of front frame F. Note how the frames slip back by distances db and df at the start of a push or pull phase. During the time ts needed to switch the motor direction UTOPUS is almost at standstill.*

Table 1. Example real world measurements of slip and speed which result in an effective velocity ev =175 m/h.

Shaft extension *d*	Average slip distance *db* of back frame *B*	Average slip distance *df* of front frame *F*	Time for full extension / contraction *t*	Time to switch motor direction *ts*
2 m	0.1 m	0.15 m	17 s	1 s

3. Experimental setup

To evaluate the suitability of the UTOPUS traction mechanism for the exploration of steep and difficult terrain in planetary exploration, we conducted a series of tests on artificial mounds of regolith with an UTOPUS model which was designed with characteristics which are normally associated with planetary missions, like compactness and low weight. This section discusses the different aspects of the experimental setup.

3.1 Crampon and vehicle configuration

The UTOPUS traction mechanism is based on crampons which penetrate the ground and use subsurface soil strength to provide tractive resistance. The crampons used here consist of a main circular steel bar to which two circular steel tines are attached which penetrate the soil. The main bar is 35 x§ long, has a diameter of 2 cm and is attached by a horizontal hinge to the back of its frame. Both tines have a diameter of 1.2 cm. The outer tine, which is farther from the hinge, is 31 cm long and the inner tine is 23 cm long, see Table 2. The tines are attached to the bar such that when the bar is in horizontal position, the bars point down and backwards at an angle of roughly 70 degrees from horizontal, to help the tines rotate into the soil, see Figure 5. A preventer, which is not shown in Figure 5, prevents the bar from rotating through the horizontal plane. When the bar is in the horizontal plane it is about 10 cm above the ground. At this point the depth in the ground is about 19 cm for the longer outer tine and about 12 cm for the shorter inner tine.

Fig. 5. *Crampon design. The hinge at the back of the frame is indicated by a blue circle.* ***Left****: The crampon before entering the ground.* ***Right****: The crampon anchored in the ground, resisting the drawbar pull F.*

Table 2. Design parameters of the crampons.

	Length	Diameter of tine	Maximum depth in ground
Central bar	35 cm	2.0 cm	
Long outer tine	31 cm	1.2 cm	19 cm
Short inner tine	23 cm	1.2 cm	12 cm

For a given type of soil the breaking force of a tine in the soil depends primarily on the width and depth of the tine in the ground and its inclination, as discussed extensively by Hettiaratchi et al. (1966) and Godwin and Spoor (1977). As a rule of thumb, a thin vertical tine offers a high resistive force at low penetration cost, particularly if the tine is arranged such that any soil failure will automatically push it deeper into the soil, thus increasing its force resistance. The breaking force also depends on soil properties, which have a high spatial variability. Relevant soil properties include soil moisture content, soil clay content, and whether the ground is plowed or unplowed. Table 3 gives exemplary measurements from agricultural cultivation, where the front crampons are anchored in unplowed soil, and the rear crampons are anchored in plowed soil. The crampons are the same as used for the present experiment and consist of metal tines of 1.2 cm diameter, but the hinge was a bit closer to the soil and the tines penetrated the soil to a depth of 20 cm.

Table 3. Exemplary measurements of resistive force of tines at 20 cm depth. Measured values will vary greatly with soil conditions.

Soil type	Maximum resistive force of tine at front frame in unplowed soil	Maximum resistive force of tine at rear frame in plowed soil
Clay	320–340 *N*	270–240 *N*
Sandy loam	200–185 *N*	135–120 *N*

The crampons need to be heavy enough so that they penetrate the soil when they move backwards. The crampons described here have a weight of 1.1 kg. Additional weight for the penetration is provided by the frames. The entire machine used for the present experiment weights 42.5 kg, including a 4 kg weight which was added to the front for balance halfway through the experiment.

The specific UTOPUS model used in this experiment was driven with an asynchronous 4-pole motor of 180W. The cogwheel travelled for a length of 1 m on the extensible shaft. Measured from the hinges of the crampons the distance between the front and rear frames was 163 cm when fully extended, and 63 cm when fully contracted. The front frame and the rear frame each had two crampons at a distance of 30 cm, for a total of four tines at the front frame and four tines at the back frame. To prevent the back of the shaft from sliding over the ground, the back of the shaft was provided with additional wheels which did not provide traction. While the agricultural cultivator in Figure 3 is steered with a flanged wheel attached to the front of the shaft, no steering was provided to the model in the present experiment, since one of the questions of this experiment was to assess how straight UTOPUS will climb without steering intervention.

3.2 Choice of terrain and vehicle maneuver

To assess the ability of UTOPUS to explore an extraterrestrial landscape, we consider the task of climbing and descending surfaces of loose regolith with inclinations of 25–40 degree, at the critical angle of repose. The experiment was conducted on small artificial mounds at Finca Son Duri, Vilafranca de Bonany, Spain, taking advantage of concurrent works to excavated a 2 m deep trench for a major gas pipeline through agricultural farm land. The mounds were created as follows: after removing the topsoil and storing it separately, subsoil from a depth of 20 cm to 2 m was excavated, poured on mounds to a height of 2 to 3 meters along the trench, and allowed to settle for over three months. The little rainfall during the period of settlement caused no visible signs of erosion on the mounds, and no vegetation established itself on the mounds.

For the experiment described here we chose two mounds of 2 m height, 7 m width at the base, and an inclination of 25–40 degrees, close to the critical angle of repose. The most common inclination experienced by the vehicle during the actual climb was 30 degrees. Soil composition was 3% gravel and larger stones, with the remainder being composed as follows: 15% sand, 30% silt and 55% clay. Both mounds had an elongated ridge at the top which the vehicle had to cross.

The challenge of climbing and descending the mound can be subdivided into several sub-challenges (Figure 6):

1) Start the climb at the base of the mound. The vehicle needs to align itself with the new axis of advance. While the shaft initially extends forward horizontally into the mound, the front frame needs to translate this into an upward motion.
2) As the front frame starts to climb, a concavity is formed under the shaft, which might pose problems to the ability of the crampons to find a good grip on the ground.
3) Climb the face of the mound in a steady line, taking into account surface irregularities and obstacle like rocks.
4) Overcome the ridge on top of the mound.
5) Descend safely.
6) Overcome the concavity at the base of the mound.

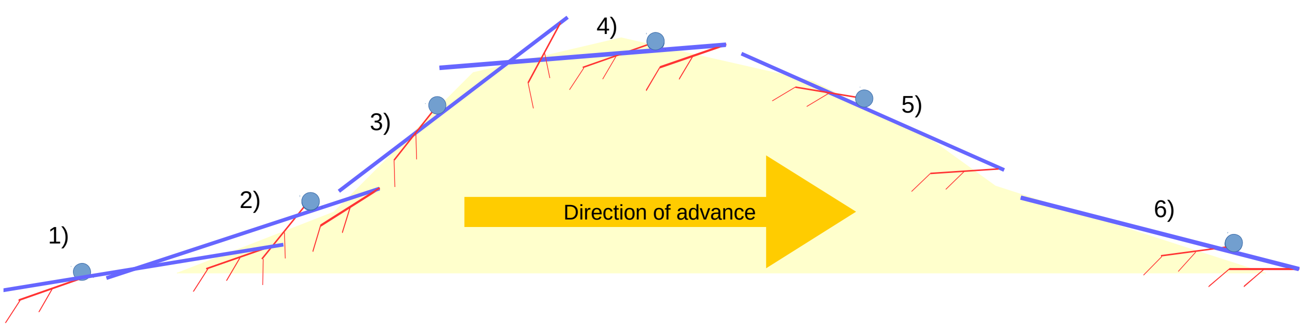

Fig. 6. *Schematic drawing of UTOPUS mound climbing maneuver.* ***1)*** *UTOPUS approaches the mound and initiates the climb.* ***2)*** *UTOPUS passes the concavity at the base.* ***3)*** *UTOPUS climbs the side of the mound in a steady line.* ***4)*** *When the front end of UTOPUS extends beyond the surface, UTOPUS swings into a horizontal position.* ***5)*** *UTOPUS descends safely in a controlled descend.* ***6)*** *At the base UTOPUS passes another concavity.*

4. Description of the experiment

We conducted ten trials. Four times UTOPUS completed the entire maneuver with success. One of these successful trials is shown in Figures 7 to 13[1]. Twice UTOPUS reached the top of the mound but did not swing over, i.e., the shaft pushed into the air. The front crampon could not engage the ground, and the two trials had to be aborted as failures. After these two failed attempts an additional weight of 4 kg was attached to the front end, and the problem did not reoccur. Due to the uneven terrain, UTOPUS occasionally reached a lateral inclination of about 30 degrees and on two of these occasions rolled over, ending the trial on its back. The precise inclination of the device at the moment it rolled over was not recorded. Twice during the ascent UTOPUS reached a position where the soil was so loose that the crampons of the rear frame would not find any soil resistance even when penetrating the ground to the preset maximum depth (19 cm for the outer tine, 12 cm for the inner tine). That is, the rear crampons slid back and forth through the soil for the entire length of UTOPUS as if moving through water. As UTOPUS could not advance any further, these two trials had to be aborted as failures.

Below a detailed description of UTOPUS behavior during the sub-challenges described above:

1) At the base of the mound the front of the shaft initially pushed against the mound until the shaft was aligned with the new axis of advance. As the rear crampons were firmly anchored, UTOPUS generated sufficient traction in all 10 trials to simply push the front end of the shaft through the soil and on top of it, without providing any specific engineering solution.
2) When passing the concavity at the base of the mound, the rear frame would occasionally slip backwards for a longer distance before finding firm soil. While this slowed the vehicle down, there was no indication that the concavity forms a significant problem to this method of locomotion per se.
3) UTOPUS reached the maximum inclination of the mound. The crampons slipped back further than on level ground when trying to penetrate the soil, reducing the overall speed. On two occasions both crampons on the back frame failed to find any solid soil at the maximum depth of the crampons, and the vehicle was unable to advance further, leading to two aborted trials. In all other cases the crampons became firmly anchored and provided the vehicle with enough traction push through most irregularities in the terrain. Rocks of 20 to 30 kg were simply pushed forward and aside. However, the irregularly undulated topology of the ground resulted in an overall path which was not straight, and on five occasions the vehicle passed not as intended over the top of the mound, but to one side of the top, reaching a lateral inclination of about 30 degrees. On two of these occasions the vehicle rolled over and landed on its back, leading to aborted trials.
4) When UTOPUS reached the top of the mound it needed to swing over so that the crampons of the front frame could engage the soil. At the first two occasions when UTOPUS reached the top it did not swing over. The front crampons were groping in the air, the vehicle could not advance further, and the trials had to be aborted. Thereafter we attached an extra weight to the front of the shaft. At all subsequent trails, when UTOPUS reached the top, it would swing over and descend on the far side. While crossing the top, the shaft of UTOPUS slid over the soil and rocks. This did not have any noticeable effect on the motion dynamics and did not interfere with the drive system.
5) On the four occasions that UTOPUS reached the far side of the mound, it proceeded to decent without incidents. It did not slip and it did not move faster than programmed.
6) UTOPUS also passed the concavity at the base of the far side without incidents.

[1] Video documentation can also be found at http://sedewa.com/utopus-climber.html

Fig. 7. *At the beginning of a climb UTOPUS pushes the shaft into the mound. The crampons generate sufficient traction to allow the vehicle to align itself with the new axis of advance.*

Fig. 8*: As UTOPUS begins to climb, the distance between the shaft and the ground increases at the concavity, such that the crampons have less contact with the ground.*

Fig. 9*: UTOPUS has overcome the concavity. As it climbs it pushes obstructing gravel and rocks aside. Note that rock fragments tend to accumulate on the surface of debris flows due to granular convection.*

***Fig. 10. Left**: UTOPUS in full climb. **Right**: Reaching the top, the front end is temporarily suspended in the air. A 4 kg iron ballast is visible on top of the front end.*

***Fig. 11**: After a few more centimeters of extension and thanks to the extra ballast the front end becomes too heavy. UTOPUS swings over the edge such that the front crampons can engage the soil.*

***Fig. 12.** UTOPUS has overcome the top ridge and starts to descends on the far side. **Left:** As UTOPUS descends, its rear end is momentarily lifted into the air and the shaft slides over and through the ground without any noticeable consequences. **Right:** Where moving parts touch the ground, small avalanches are created. The crampons keep the vehicle stable and it never slips.*

Fig 13: *At the bottom of the far side another concavity is overcome. Note how the vehicle has sufficient traction to push through obstructing ridges of soil at the bottom of the mound.*

5. Conclusion

We found that UTOPUS is in principle able to climb and descend a slope of heterogeneous dust, gravel, and broken rock at an inclination of 25–40 degrees, close to the critical angle of repose. Despite the fact that the vehicle motion creates small avalanches of sand and gravel, the crampons hold firm and are able to generate sufficient traction and stability to push and pull the vehicle forward. We have not witnessed a single occasion where the vehicle slid, either in the ascent or descent. We also observed that UTOPUS was able to push small obstacles like little ridges of sand or rocks out of the way, thus creating a smooth path of advance. However, due to the uneven topology, the overall path was not straight and requires active steering.

Our initial concern that concavities and bulges would constitute obstacles to inching locomotion with an extensible shaft was unfounded. UTOPUS traversed every concavity without noticeable problems, though we acknowledge that this might be due to limited variation in the experimental setup. Initial problems at the top of the mound were overcome by rebalancing the vehicle. By providing additional weight to the front end, UTOPUS would swing over the top of the mound as intended.

There was a clear problem with lateral stability in the current configuration. At two instances the vehicle reached a position where lateral inclination was about 30 degrees and the vehicle rolled over. This shows that the crampons by themselves cannot withstand a torque about the central axis. As the width of the vehicle at the crampons was only 30 cm, a wider vehicle design might offer an immediate solution, at the cost of vehicle compactness.

A more serious problem was exposed by the two maneuvers where the rear crampons could not find any resistance in the ground during the climb. This might be due to the fact that the angle was close to the critical angle of repose, but also due to the specific local composition of the heterogeneous material of which the mound was composed, and the fact that after the first trials the soil had lost some of its strength. The crampons had a mechanical preventer which did not allow them to penetrate the ground to a depth of more than 19 cm, to prevent excessive torque on the hinges. The crampons might have found resistance if they had penetrated deeper, but the possibility remains that deeper soil layers would have exhibited the same structural weakness, a question which can only be answered with further experimentation. We note that this problem is of particular importance in low gravity where soil strength can be expected to be even lower.

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