

An Insight on Mud Behavior Upon Stepping

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Abstract—In this research we show a characterization of mud behavior under vertical stepping. We showed that mud stiffness can vary 45-fold and the energy spent to generate equivalent impulse can vary 2-fold depending on the mud water content, but also that stepping faster on mud leads to lower peak forces and higher energy consumption. Next, we showed that the peak force generated can be increased by 33% by changing the foot stiffness, but is reduced by 18% if stepping is repeated on the same spot. We then demonstrated how force control can be used to achieve identical force profiles on very different muds. These results will help to design mechanical parts or control strategies for legged robot locomotion on mud.

Index Terms—Field robot, force control, flowable ground, legged robot, mud.

I. INTRODUCTION

WET cohesive materials are ubiquitous in nature (forest soils, mudflats, marshes, littorals, estuaries, wet fields) and are challenging to traverse. The ability to traverse these environments is of particular interest in robotic missions such as search and rescue in forests, muddy fields, and mudslides; for agriculture on wet soils (e.g. rice fields); for exploration or excavation of materials with a minimal environmental impact, or for monitoring biodiverse environments. Currently, the only machines at our disposition to access such environments are large machinery like tractors, ATVs, or tracked vehicles which are heavy and have continuous contact with the ground. To reduce the impact on natural environments, and to easier access to unstructured areas, it is thus necessary to develop tools that are lightweight and agile to avoid and preserve natural obstacles. Legged robots are particularly well suited for that as they are lighter than human-driven vehicles, the legs enable nondestructive discrete contact points with the environment and the compaction resistance of soft material piling up in front of wheels/tracks can be avoided. It was shown that legged robots combine the most advantages for traversing natural environments but present shortcomings in soft grounds compared to tracked robots [1]. Indeed, legged robotics research has mostly

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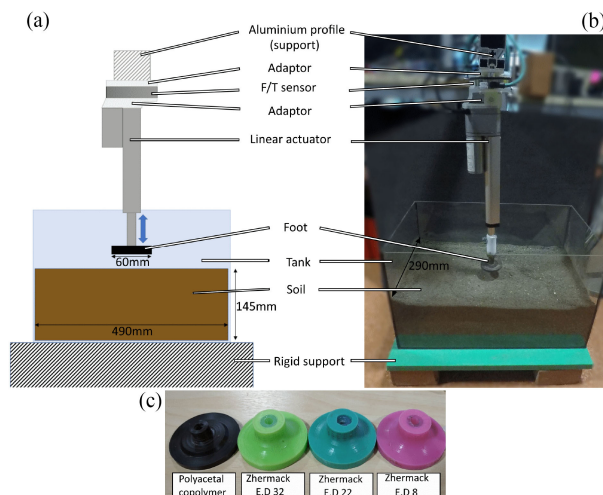


Fig. 1. (a) Schematics of the experimental setup. (b) Photo of the experimental setup. (c) The four different feet used. Foot stiffness increases from right to left.

focused on hard flat terrains, and only recently addresses locomotion on rough/uneven terrains (debris, rocky slopes) [1]. Locomotion on soft grounds is seldom an object of robotics research and focuses primarily on sand or other granular media [2]. Wet, cohesive materials are rarely studied in the context of robotics research and even less in legged locomotion. One possible explanation is the increased locomotion complexity these environments present: as we demonstrate in this letter, they are cohesive, resist extrusion of the foot, are plastically deformable, and their behaviors depend on water content. In this letter, we aim at reducing the shortcomings legged robots have on wet flowable grounds, by investigating the behavior of mud upon stepping using a vertical foot/mud intrusion setup (Fig. 1, supplementary video). This work aims at providing an insight into the topic to help the design of robot legs and their control for efficient and/or effective locomotion on mud.

II. RELATED WORK

Legged locomotion on flowable soils is a complex and energy-consuming activity for humans and animals alike. It is even more for legged robots, which rather recently started to demonstrate agile locomotion on hard grounds [3], [4]. In general, as we will demonstrate, neither terramechanics nor legged robotics have solved the challenge of stepping on a wet, cohesive flowable material. Terramechanics [5], which studies the interaction between soil and wheeled/tracked vehicles takes a traction perspective, and its applicability is limited to wheeled/tracked vehicles, which only slightly sink into the soil, have continuous

contact with the ground, are heavy, and reach high tangential velocities compared to an animal walking on mud. These use cases make its principles unsuitable for legged robots which are lighter, with discontinuous contacts, and move at lower speeds where traction and slippage play a smaller role than sinkage. Yet, terramechanics derived some pressure-sinkage models, such as Bernstein's [6], Bekker's [7] or Reece's [8]. These are useful to model different materials but require several parameters, making them more accurate, but complex and terrain-specific. [9] reviews the soil models and parametrization methodologies, but is aimed at wheels/tracks-terrain interaction, and, underlines the high variability in the models obtained for soil characterization. This demonstrates the complexity of deriving a soil model, and shows the emphasis terramechanics research put on tracked/wheeled vehicles. The variety and complexity of soil models are obstacles to their applicability to mobile robots, which may traverse environments in which each step will be different.

On the other hand, legged robotics research rarely covers interactions with wet, cohesive, flowable soils. The review on locomotion robophysics reviews a wide range of robot models and experiments aiming at understanding principles of locomotion and largely focuses on dry granular media [2]. Legged robot locomotion on dry sand, for example, was studied [10] [11], but the derived principles are applicable to dry granular media, which are cohesionless. Terrain classification studies also were done on dry materials, where a robot can classify the type of soil [12]. Some attempts were made to have robots walk on mud, but they were either made on a shallow layer of mud, where the solid ground under it is used as support [3], or based on high-speed strokes of rotating legs. A range of robots based on this principle was developed, stemming from the RHex hexapod structure with 1 degree of freedom (DoF) per leg [10], with end effectors evolved into Whlegs [13], reconfigurable legs/flippers [14], [15], Ninjalegs [16], or variable stiffness legs [17]. Some of these robots demonstrate an ability to traverse mud, but the locomotion based on rapidly rotating 1 DoF actuators doesn't allow advanced gait planning or step placement to pass obstacles or preserve the environment. More complex and versatile robots with several DoF per leg represent a great opportunity to overcome more challenging terrains and to preserve the traversed environment. However, adding several DoF per leg also increases control complexity, which is even more challenging in muddy environments.

Most legged robotics research on soft terrains addresses control of robots, especially gait control using one of two approaches: control using a soil model, or using a model-free controller. For example, a soil model assuming that force increases with sinkage following a power law was used on a hexapod walking robot which corrected its attitude using force information [18]. Similarly, active compliance was used on a six-legged robot where the body orientation was kept fixed and leg sinkage was controlled [19]. More recently, a genetic algorithm was used to simulate the gait generation of a quadruped robot on sand using a non-linear model for intrusion forces in sand [20]. Model-free controllers, are also mostly based on force control, for example, in [21], a simple model-free force controller enabled a robot

to balance on a variety of grounds. Simulations on a hopping system suggest that impulse control permits motion on terrains with unknown properties, including dissipative grounds [22]. Also, [23] demonstrates a model-free reinforcement learning controller able to maneuver a four-legged robot through unstructured environments, including a shallow layer of mud, which allows support on the solid underlayer, contrary to deep mud. In [24], a hybrid ground learning and active compliance control was developed to enable a robot to walk on both wood and sponge, but was not demonstrated on cohesive media. As shown here, most research on legged locomotion on soft grounds dealt with stabilization or attitude control applied at the whole-body level. However, whole-body locomotion encompasses complex control problems which would benefit from a better understanding of foot/ground interactions. We hence propose to focus on simplified setups investigating foot/ground interactions.

Contrary to whole-body locomotion research, some studies investigate a single control or mechanical parameter. [25] analyzed the cost of transport (CoT) and velocity of two gaits in a fluidized sand bed and found that retracting the leg out of the flowable material was the most effective and efficient way of running. [26] suggests that using a circular, flat-bottomed foot on sand enables to reach higher force. For these reasons, in our experiment, we will use flat-bottomed, circular feet.

In the above literature review, little research investigated the behavior of mud upon stepping. Most research in terramechanics focuses on wheels or tracks interaction with soil, and legged robotic research mainly focuses on robot stability on different soils. Some of the above approaches demonstrate good results in terms of stability, however, few showcased locomotion on flowable soils, and none attempted characterization of wet soil or used agile locomotion strategies. The contribution of this letter is the characterization of the behavior of mud upon stepping and the investigation of parameters having an impact on bearing capacity, but also the demonstration that a simple force controller, based on qualitative knowledge of mud behavior can be used to traverse different muds. These results will be useful to develop an understanding of the mud behavior and bolster the design of mechanical parts and controllers to develop robots for agriculture, environmental monitoring, search and rescue, exploration, and resource extraction.

III. MATERIALS AND METHODS

Mud has properties changing in space and time, due to its infinite number of possible compositions (percentage of clay, silt, sand, gravels, organic matter, water, compaction). Therefore, a general model for mud is complex to develop and probably unpractical. Hence our approach staved off deriving an accurate and general model and instead analyzed the qualitative behaviors which could be generalizable to different muds. We performed experiments intruding circular feet into muds: intrusion at constant speed on two different soils, with different feet, at constant speed with different water content, and force-controlled steps on soils with different water content (Table I). For each

TABLE I
OVERVIEW OF THE EXPERIMENTS PERFORMED

Exp. #	Parameter varied	Values of parameter varied	Const. parameters	Num of experiments	Goal
1	Speed of intrusion	[10, 20, 30, 40, 50] mm/s	Water content, foot	10 per condition (total: 50)	Investigate whether the speed of intrusion impacts the maximum achievable force
2	Speed of intrusion	[2, 3, 3.8, 4.3, 8, 14, 20, 34, 48] mm/s	Water content, foot	10 per condition (total: 90)	Similar to exp.1, with higher water content, to see whether the speed of intrusion impacts muds with different water contents differently.
3	Foot material	Polyacetal copolymer, ZED 8,22,32	Water content, speed	10 per condition (total: 40)	Investigate whether foot stiffness impacts the maximum achievable force.
4	Water content	[0, 5, 10, 15, 20, 25, 30, 35, 40]% dry soil mass	Speed, foot	10 per condition (total: 90)	Investigate the evolution of the soil stiffness and retraction force with water content.
5	Repeated stepping	3 steps	Speed, foot, water content	10	Investigate whether mud's bearing capability is reduced after stepping, and by how much.
6	Water content	[0, 20, 30, 35]% dry soil mass	Foot, force controller (only in experiment 6)	18 per condition (total: 72)	Demonstrate the feasibility of force control on different muds using the same model-free controller.

experiment, the measurements of interest are the sinkage and force.

For these experiments (see Fig. 1), a linear actuator Firgelli FA-PO-35-12-6" was used to step on mud. Four feet of different stiffness (rigid plastic (polyacetal copolymer) as well as silicones Zhermack Elite Double- ZED 8, 22, and 32) were mounted on the actuator (Fig. 1(c)). Each foot is circular with a diameter ϕ 60 mm (28.3 cm²). The silicone feet were cast with a rigid mesh in the upper part to allow a rigid connection between the foot and the actuator. The mud was garden soil saturated with water. Control was implemented on an Arduino Uno (Arduino AG) and data was recorded using Matlab Simulink (MathWorks inc). Force was recorded using an ATI Serial Axia Force/Torque (F/T) sensor. For each experiment, we recorded the position, vertical force, and calculated power. Moments and lateral forces were measured and considered negligible.

When the speed of intrusion was studied (Figs. 4 and 5), we saturated the soil with water and intruded the foot at different speeds until a set sinkage. Experiments 1 and 2 were performed on muds with different water contents because the actuator's limitations prevented very low speeds on harder soil. For investigating the effect of feet stiffness on the force/sinkage relationship, we use a PID velocity controller with position condition intruding the foot to a predefined depth at a constant speed, to compare the required force for intrusion at identical depth.

For investigating the effect of water content on bearing capacity, the soil was first dried on the ground for 5 days and then sieved with a 4 mm sieve. 20 kg (20.6 L) of dry soil was then placed into the tank and slightly compacted by placing a 4 kg weight (with 44 cm² surface area, leading to a 8.9 kPa pressure). We then shuffled the upper part of the soil to reduce the surface compaction. For each experiment, the foot was penetrated into the soil at a constant speed (10 mm/s). Between experiments, the soil was mixed, compacted, shuffled, and evened out. Altogether we performed 10 experiments per water content, in 9 different conditions (Table I). After each addition of water, the soil was mixed to have homogeneous properties. A 90 N threshold was set to protect the experimental setup.

The 1 DoF experiment did not allow generating lateral forces, responsible for the forward motion of a legged device. However, we argue in this letter that on mud, slower locomotion is preferable. Since slower locomotion generates lower lateral forces, the limitations of the setup do not play a significant role. Additionally, in deformable grounds, legs sink and are laterally supported by a column of mud. This reduces the risk of slippage, as observed in cows which reduced speed and increased step length and leg inclination at contact in deep mud [27].

Following the mud characterization, we performed stepping experiments on the mud by controlling force of the leg, using the ZED 22 foot because of its higher performances in other experiments. To simulate the profile of the vertical Ground Reaction Forces in legged locomotion, the positive half cycle of a sinusoidal wave was commanded, with a 4 s duration and 30 N amplitude. This controller (see Fig. 2) allows generating the three phases of the step: landing, support, and lift-off. When in the force mode, two different PID controllers are used for the two nearly-linear behaviors of mud; one with a steep slope for decreasing force, and one with more moderate slope for increasing force (see Figs. 4, 7, and 8). Then, the gain adaptation block varies the gains of each force controller depending on the derivative of force command by a multiplying factor computed as in (1).

$$\alpha = \frac{\arctan(\dot{u} - 1) + \pi}{2} \quad (1)$$

The adaptation of gains enables to complement the shift of PIDs by making PID 2 less aggressive as the command flattens, and on the contrary, making PID 3 less aggressive when the command sharpens toward negatives. This way, despite the high variability of soil stiffness, we can achieve smooth force increase, and prevent any excessive reaction when force command decreases, especially when the slope of force/sinkage relationship is very steep.

IV. RESULTS AND DISCUSSION

A. Going Slower is More Efficient

Experiments 1 and 2 (see Table I) investigated the effect of speed of intrusion on forces generated on mud. The impulse of

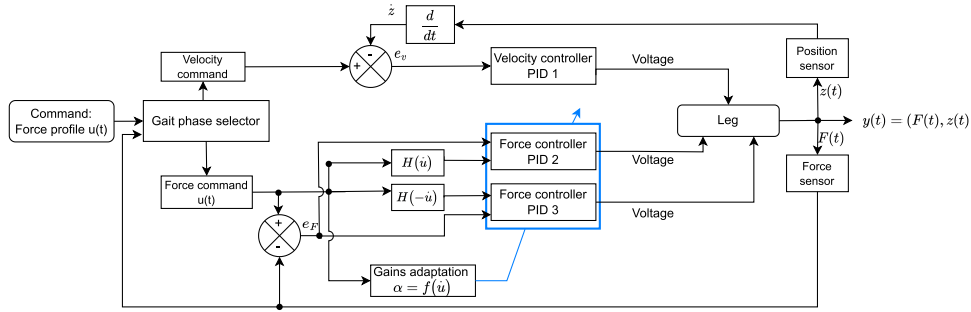


Fig. 2. Step controller. The gait phase selector decides whether the step is before landing, during support or lift-off of the foot based on a force threshold (1 N), and outputs a velocity command or a force command. First, a downward velocity command is sent, then, if force is higher than the threshold, the force profile is commanded, and when force goes below the threshold again, an upward velocity command is sent. The velocity PID controller is following the set velocity command until the force controller relays (landing phase) or until a position is reached (lift-off phase). When in force command mode, two Heaviside blocks activate PID 2 or 3 depending on whether the force command is increasing or decreasing. Additionally, each controller's gains are adapted based on the derivative of the force command.

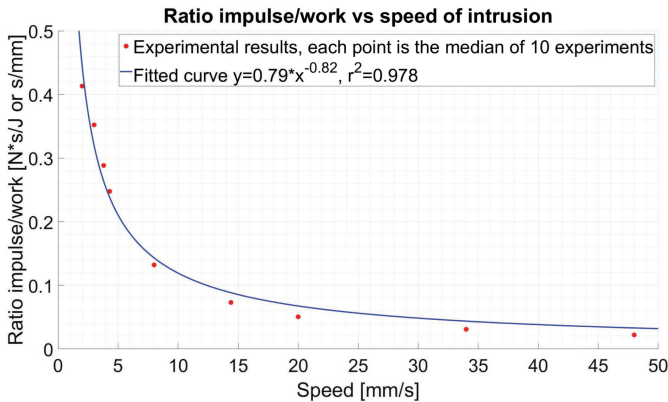


Fig. 3. Ratio impulse/work vs speed. The ratio was computed by dividing the impulse (Newton-Cotes integration of force overtime, only during the movement phases) by work (Newton-Cotes integral of force over sinkage).

a step onto the soil is defined as the integral of force overtime. Work, which represents the energy lost in the deformation of soil (and is, contrary to solid, elastic deformations, irrecoverable), is computed as the integral of force over sinkage. If we want to maximize the vertical momentum while minimizing the energy lost in soil deformation, we may want to increase the following ratio:

$$\frac{Impulse}{Work} = \frac{\int F dt}{\int F dz} \quad (2)$$

which has the unit of s/m, or inverse of speed. In equation (2), z is the distance between the current position and the position where the first non-zero force was detected (similarly for t). Let us consider the intrusion phase. As shown in Section II, there exist a variety of soil models. Despite being accurate, these models are complex and therefore harder to apply, especially on a natural ground where the material parameters may vary. For these reasons, we chose to simplify the model as much as possible to both increase its generalizability and to simplify its parameter estimation, at the cost of reduced accuracy. One of the simplest models is Bernstein's, i.e., $F(z) = k \cdot z^n$, where $F(z)$ is the force as a function of sinkage, k and n are constants depending on the soil [6]. Observing Figs. 4(a) and (b), 7, 8

and Table II, we can notice that during the intrusion phase, the relationship between force and sinkage is almost linear. Hence the model can be simplified to

$$F(z) = k \cdot z \quad (3)$$

Since we use a constant speed of intrusion, and force increases linearly with depth (3), force increases linearly with time:

$$Impulse = F_{max} \cdot \frac{t}{2} \approx \frac{kzt}{2} = \frac{kz^2}{2v_z} \quad (4)$$

where $v_z = \frac{z}{t}$ is the vertical speed, and we have

$$Work = F_{max} \cdot \frac{z}{2} \approx \frac{kz^2}{2} \quad (5)$$

which gives

$$\frac{Impulse}{Work} = \frac{1}{v_z} \quad (6)$$

This relation is also observed in our experiments, as witnessed in Fig. 3. This result can be understood as follows: being static on mud requires no energy (no work) and still generates impulse, driving (6) to infinity. The same impulse can be generated by several intrusions at the same depth, deforming soil on each step. To keep a constant altitude, a robot must compromise between stepping frequency and energy efficiency, at least for what concerns mud deformation. Note that this applies if we withdraw the foot as soon as it reaches the maximum force. On a mobile robot bearing its own weight, the efficiency could even get better at very low speeds. Indeed, as witnesses Fig. 5, after the movement has stopped (at peaks), the force suddenly drops. The slower the leg sinks, the smaller the difference between the peak force and the steady-state force. If we let the robot sink under its own weight (case when the speed is excessively slow), no mechanical power is required, but also, we don't have any 'excess' peak force, which is otherwise wasted mechanical work. When pulling the leg out of the mud, some energy is still required, the other legs are bearing more weight and sinking deeper.

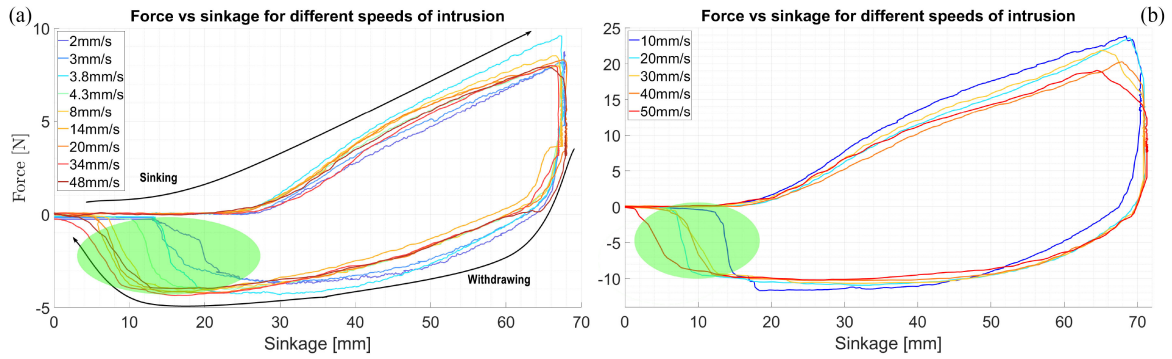


Fig. 4. (a) Force vs sinkage for speeds from 2 mm/s to 48 mm/s. The graph is read clockwise: sinking leads to positive forces (left to right) up to the peak force and withdrawing leads to negative forces (from right to left). The green area marks the breakage of the suction effect. Each curve is the median of a set of 10 curves. Interquartile ranges (IQR) were omitted for readability. (b) Similar experiment with lower water content, in steps of 10 mm/s.

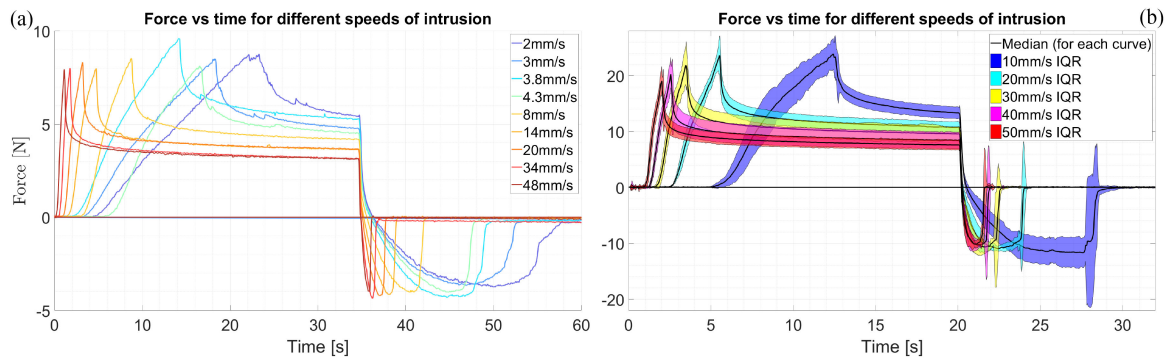


Fig. 5. (a) Force vs time for speeds from 2 mm/s to 48 mm/s, corresponding to Fig. 4(a). It consists of intrusion at a constant speed, a pause until the 35th second, and retraction. Each curve is the median of 10 experiments. IQRs were omitted for readability. (b) Force vs time for speeds from 10 mm/s to 50 mm/s, corresponding to Fig. 4(b). The experiment consists of intrusion at a constant speed, a pause the 20th second, and retraction. Each curve is the median of a of 10 experiments.

B. Going Slower Increases Forces

Fig. 4 shows the force vs sinkage for different speeds. Experiments in Fig. 4(a) were performed on mud with more water than those in Fig. 4(b). Both figures show a higher force for the lower intrusion speed (shear-thinning), and Fig. 4(b) shows that the mud with a lower water content resists intrusion more, and its resistance is more dependent on speed. While withdrawing, we can see that force first drops to zero with little movement because of the plastic deformation of the mud. Then, withdrawing further creates a suction under the foot which leads to negative, pulling forces. When the air gets under the foot, the suction is broken and force abruptly returns to zero (green areas in Fig. 4). For the two water contents tested we observe an absolute ratio of 2 both between the maximum intrusion force and suction force. However, the suction continues across a longer extrusion when the water content is higher (Fig. 4(a)).

This result complements the previous one: on top of decreasing the energetic cost of locomotion on mud, lower speeds also lead to higher forces, reducing further the mechanical work spent on deforming the soil. If the goal of a mud walking robot is efficiency or reduced environment deformation, reducing velocity appears to be a promising strategy. Nevertheless, legged robots

need to maintain base torque (and power) in their motors to stand still. Thus, decreasing the robot's speed increases the time a robot takes to perform a task and will in turn lead to higher energy consumption. Further experiments studying the CoT on a legged platform are needed to find an optimum.

C. Stiffness of the Foot Matters

As can be seen in Fig. 6, the feet with the average stiffness (ZED 22 and 32 feet) generate higher forces for the same sinkage. More precisely, the ZED 22 foot reaches 33% higher force than the ZED 8 (37.6 N vs 28.2 N). However, this advantage is mitigated by the higher force required when withdrawing the foot. The feet that create the highest force during sinkage also require more force when withdrawing from the mud (Fig. 7).

A possible explanation for the force dependence on stiffness is that, compared to the rigid foot, the ZED 32 and 22 feet deform more under the application of force, hence avoiding high-pressure concentrations that cause the failure of the mud. When the foot is too soft (ZED 8), the deformations are so large that the projected surface area of the foot decreases significantly and the pressure is higher, causing failure of the mud. This new finding adds to previous findings relating to the shape of the

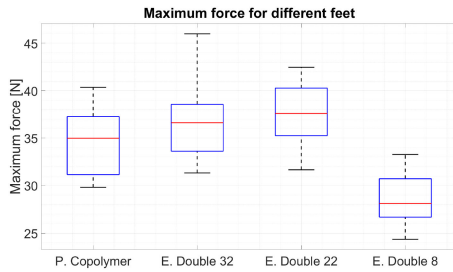


Fig. 6. Maximum force generated by the feet for a same step. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent for the maximum forces reached in Fig. 7.

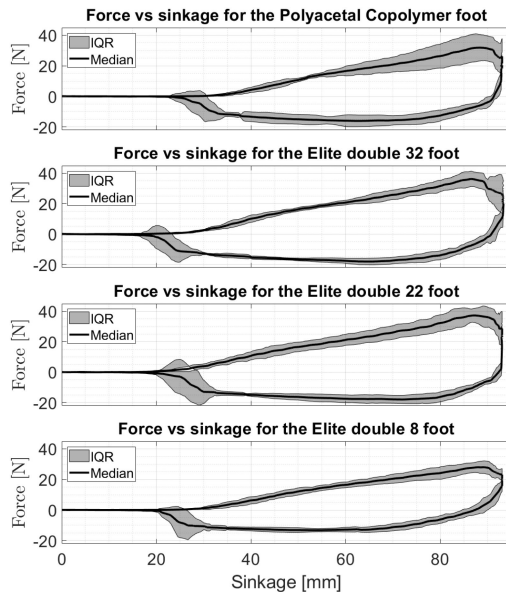


Fig. 7. Force vs sinkage for the four feet. Each curve is the median of 10 similar experiments.

foot [26] for determining the intrusion force. When a robot is intended to walk on soft grounds attention should be paid to foot stiffness. It is known that on hard grounds, low foot/tire stiffness results in more energy to move. It is consequently advisable to adjust the foot stiffness depending on the ground the robot walks on.

D. Higher Water Content Reduces Mud's Bearing Capacity

The force/sinkage curves for different water contents are displayed in Fig. 8. The slopes of these curves, assuming a linear relationship (3) are plotted in Fig. 9, and the coefficients of determination (R^2) are presented in Table II. When water weights 0 to 20% of the soil mass, the soil gradually reduces its bearing capacity with (median) slopes between 8.1 and 5.9 N/mm, but with higher water content, the stiffness drops to 0.18 N/mm for 40% water content, 1/45th of the stiffness for 2 L of water. We can see from Table II that the linear model fits very well for up to 25% water content ($R^2 > 0.95$). For higher water contents, the linear model derives marginally from the experimental observations

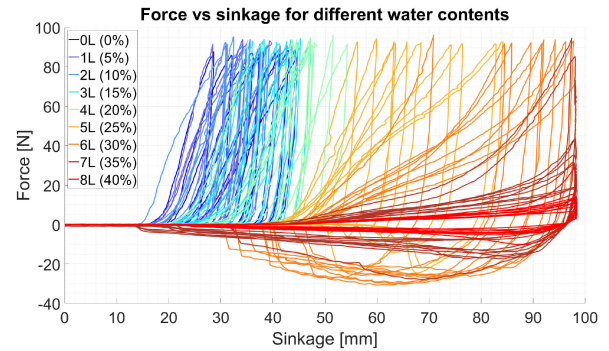


Fig. 8. Force/sinkage curves for different water contents.

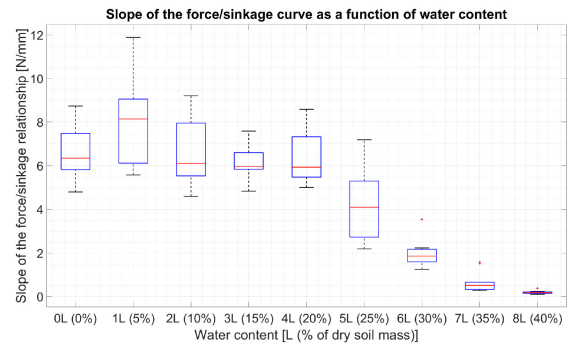


Fig. 9. Slope of the force/sinkage relationship vs water content. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent of the slopes extracted from Fig. 8. To compute the slope, we fitted a linear model between the point where 1 N is reached and the maximum force.

TABLE II
 R^2 FOR THE LINEAR MODEL FITTING OF THE CURVES IN FIG. 8 COMPUTED AS THE AVERAGE OF THE 10 SIMILAR CURVES

Water(%)	0	5	10	15	20	25	30	35	40
R^2	0.993	0.982	0.976	0.9501	0.956	0.992	0.937	0.908	0.907

but is still a good fit ($R^2 > 0.9$). This result suggests that linear controllers could be used for the landing phase.

The suction force appears after 5 L of water (25% dry soil mass), reaches its maximum at 6 L (30%), and then decreases as the mud fluidizes (Fig. 8). This suction could be minimized by an anisotropic design, i.e., a foot with a different shape for intrusion and extrusion. On a legged robot, suction from the retraction of one foot would further increase the load and sinkage of the other feet. Gaits and feet design preventing the suction force are hence important to consider.

Finally, Fig. 10 shows that the ratio impulse/work is lower for completely dry soil, is relatively constant for water contents from 1 L to 5 L (from 5% to 25% of soil mass), and then sharply halves. This result shows that moving on dusty soil is less energy efficient than on slightly wet and cohesive soil, but efficiency collapses when water content is high.

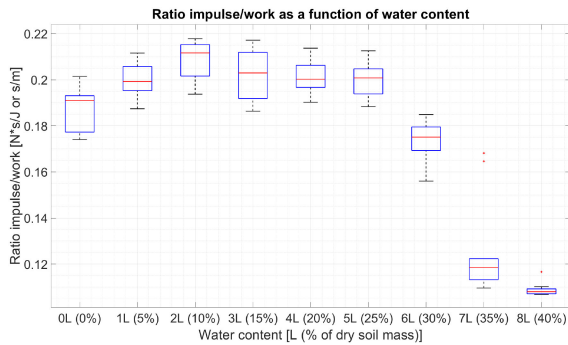


Fig. 10. Impulse/work vs water content. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent. The ratio was computed by dividing the impulse (Newton-Cotes integration of force overtime during the movement phases) by work (Newton-Cotes integral of force over sinkage).

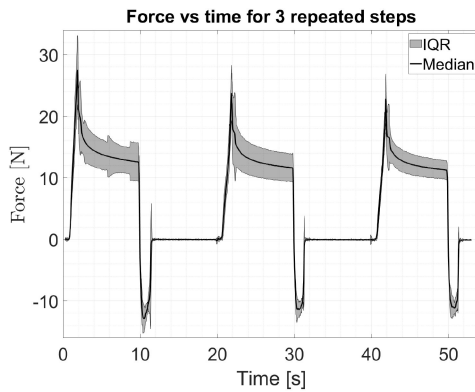


Fig. 11. Repeated steps on the same spot, at the same depth. The second step reaches a much lower force than the first, and the third reaches a slightly smaller force than the second. The black curve represents the median and the shaded area the IQR, for a set of 10 experiments.

E. Repeated Stepping Weakens the Mud

Fig. 11 shows a succession of three subsequent steps at the same depth. It can be observed that at the second and third steps the force decreases. More precisely, the median for the third peak (22.6 N) is 18% lower than for the first peak (27.5 N). This means that stepping on mud reduces its bearing capacity. It follows that for a walking robot in a natural muddy environment, gaits using new foot placement for each consecutive leg are to favor.

F. An Adaptive PID Controller Can Adapt to Varying Soils

Fig. 12 shows that the proposed stepping controller can follow the commanded force profile for most mud conditions. The controller was able to perform a step on every mud without retuning any gains, despite very different characteristics of the muds. This suggests that the qualitative model we used to design this controller is sufficient to control stepping on mud, despite the high variability in mud behavior with water content. However when the mud is too soft, the controller's performance is decreased (Root Mean Square Error, RMSE = 4.67 N, see Fig. 12). This shows the limitation of the assumption of a

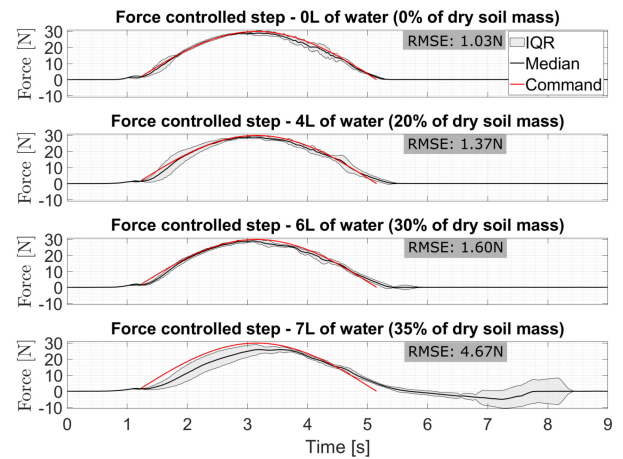


Fig. 12. Output of the step controller depending on the water content of the mud. First the foot is velocity-controlled (PID 1) up to contact, then force-controlled with PID 2 up to the peak force, then force-controlled with PID 3 until force reaches 1 N, and then is velocity controlled with PID 1. The RMSE is computed between the median curve and the command.

linear force-sinkage relationship for high water content, where a faster-reacting controller would be able to follow the command. These errors could lead to variations in the robot's attitude which could be problematic or not depending on the application.

G. Generalizability

The 1 DoF leg setup did not allow lateral forces generation, but we argue that for efficiency and environmental preservation purposes, slower locomotion, which reduces lateral forces, is preferable in muddy environments. Additionally, in deep mud, the sunked foot is anchored and prevents slippage. Therefore, we believe that lateral forces are incidental to leg-mud interaction and their absence from this study does not impede the applicability of these results to a leg with more DoF. Also, our experiments used the same soil in which the water content was varied. Interestingly, the force/sinkage relationship for intrusion is similar to that observed in sand [11], [26], loams, and muskegs [5] (linear or power function with a power close to one). However, it seems that the suction force is a particularity of mud. Mud properties are time and location-dependent and an accurate model is unpractical for a mobile robot. The qualitative behavior of mud, however, is important. Similarly, to terramechanics characterization techniques, e.g., penetrometer, bevameter [5], the method used here can be used on different muds and the observations on the dependence of the force on speed, water content and stiffness of the foot, and the weakening of mud after re-stepping are likely to be generalizable to a large variety of mud compositions. The magnitude of the variations however will likely be different in each mud. For this reason we aimed at deriving a general qualitative model instead of an accurate, terrain-specific model. Our observations can be used on legged robots, and in-situ measurement of ground stiffness or retraction force are needed to adapt the gait, using the knowledge this letter provides on the general behavior.

V. CONCLUSION

This experimental study unveiled results that can inform future work on robotic legged locomotion on mud:

- The relation between sinkage and bearing force can be approximated by a linear relationship, whose slope depends both on the intrusion speed and water content.
- The vertical impulse/work ratio is inversely dependent on speed, which means that to go faster on mud, more energy is spent per unit distance.
- Lower intrusion speeds lead to higher force, and this is more pronounced for mud with lower water content.
- A too stiff or too soft foot doesn't provide as much support force as feet with intermediate stiffness.
- At a water content of 25-35%, re-stepping in the same spot decreases mud's bearing capacity due to plasticity.
- In mud, vacuum appears below the foot and resists withdrawing until some air gets under the foot. This phenomenon appears when the water content is high enough, but lessens when the water content is too high.
- Soil stiffness collapses at high water content.
- A controller with variable gains can enable stepping on muds with different properties, with degraded performance for very fluid mud.

The 1 DoF experiment restricted variables to speed, foot materials, mud compositions, or controlling force. Future work using more DoF could vary loading strategies and explore lateral forces. Additionally, experiments on a mobile robot could focus on gaits compensating for sinkage, measure the CoT, investigate how gravity may be used to sink passively or hinder locomotion during withdrawal, when the load is relocated on the other feet. Future work could also investigate ways to cancel the suction force possibly with an anisotropic design of the foot.

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