ROBOMINERS

ROBOMINERS DELIVERABLE D1.2

NEW BIO-INSPIRED LOCOMOTION STRATEGIES CONCEPTS FOR MINING ENVIRONMENTS

Summary:
This deliverable explores the bio-inspired locomotion strategies for mining environments. In particular, we are concentrating on locomotion strategies in low-yield environments (media with the properties of both solids and fluids). This focus is chosen because first, it is a realistic environment in the mines, in particular in flooded and abandoned mines and second, because robot locomotion in low-yield environments is a novel research problem in robotics. The main body of the deliverable is a journal paper giving the overview of the animal locomotion in low-yield environments, categorization of the locomotion principles in low-yield environments and classification of the underlying physical principles of locomotion. Based on the abstract physical principles we have envisioned engineering solutions for building robots suitable for mine exploration.

Authors:
Asko Ristolainen, TalTech, WP leader
Maarja Kruusmaa, TalTech, WP leader
Simon Godon, TalTech, WP participant

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement nº 820971.

Title:	New bio-inspired locomotion strategies concepts for mining environments		
Lead beneficiary:	TalTech		
Other beneficiaries:			
Due date:	1.06.2020		
Nature:	Public		
Diffusion:	all Partners		
Status:	Final		
Document code:			
Revision history	Author	Delivery date	Summary of changes and comments
Version 01			
Version 02			
Final version	MK	15.07.2020	General comment by the reviewer: "It must be noted that the Periodic Technical Report (D11.4.1) covered some aspects not included in other deliverables. This is understandable to some extent, as it covered the overall work done in respective work packages to date, whereas most deliverables listed above were due well before the date of appraisal. In some cases, however (e.g. D1.2), this is not justified. In this particular, case all work for the WP has been completed and so the individual deliverable should have contained more detail that the Periodic Report, not the other way around." Changes made to D1.2 accordingly: • Edited Overview in section 2 to include T1.1 to the deliverable. • Added paragraph "2.1.3 Legged robot locomotion strategies" to give an overview of legged robots and its limitations. • Added paragraph 2.1.4 "Conceptual shape and locomotion strategies" to show the initial design ideas and reasoning for the concept as it was given in the RP1 technical report. • Added reference section to the Deliverable.
Revision RP1	AR	05.04.2021	

Approval status				
	Name	Function	Date	Signature
Deliverable responsible	Asko Ristolainen		31.05.2021	
WP leader	Stephen Henley		31.05.2021	
Reviewer	Claudio Rossi		24.05.2021	
Reviewer	Jussi Aaltonen		11.04.2021	
Project Coordinator	Claudio Rossi		24.05.2021	

Table of Contents

1 EXECUTIVE SUMMARY

This deliverable explores the bio-inspired locomotion strategies for mining environments. In particular, we are concentrating on locomotion strategies in low-yield environments (media with the properties of both solids and fluids). This focus is chosen because first, it is a realistic environment in the mines, in particular in flooded and abandoned mines and second, because robot locomotion in low-yield environments is a novel research problem in robotics. The main body of the deliverable is a journal paper giving the overview of the animal locomotion in low-yield environments, categorization the locomotion principles in low-yield environments and classification of the underlying physical principles of locomotion. Based on the abstract physical principles we have envisioned engineering solutions for building robots suitable for mine exploration.

2 OVERVIEW

This deliverable mostly presents work done in T1.2. "Legged robots and locomotion strategies" and proposes solutions for T1.1 "Shape and Function". As the task description says, we mostly focus on locomotion strategies in slurry, mud and slippery ground. One reason for this is because it is common in mining environment. The other reason is that it is also a scientifically novel problem statement. Indeed, there are enough descriptions and overviews of legged robots on solid terrains that we are also well familiar with. As the work description states:
"While ground robots move on the solid ground and underwater robots in water, the mining environment has both properties, e.g. it is a multiphase environment consisting of mixed solids and liquids. Amphibious robots exist that can move either in water or on solid ground but not in the environment in between, thus this problem statement is unique from a robotics point of view."

At early stages of the review, it became clear that animals in those environments do not only use legs for walking but also other locomotion strategies (e.g. crawling, jumping etc.) so we conducted a comprehensive search to analyze them all from applicability point of view.
This deliverable is presented in a form of a journal paper to be submitted simultaneously with the report to the Commission. However, in this report we also discuss and make conclusions beyond that to give a rationale to our design choices for the mining robot lab prototypes (in T1.1 "Shape and function"). The main objective of WP1 is to inform the design choices made in WP2 and WP3 (Figure 1).
This deliverable has already informed the worked carried on in WP 3, in particular T3.1. System specifications. Many decisions made there are taking into account the insights from this deliverable.

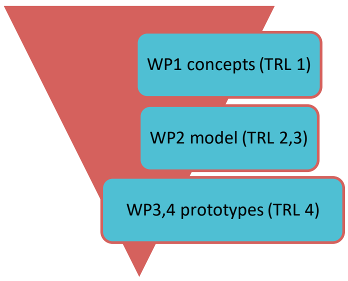

Figure 1. WP1 proposes design concepts on TRL1 to inform later design choices

2.1.1 Scope and problem definition.

Low-yield environments are environments that have properties of both solids and fluids depending on how the robot is interacting with them. If a robot applies low pressure on the low-yield material, it behaves like a solid, but once the pressure exceeds the yield stress, the material behaves like a fluid (see Figure 2). Low-yield environments are common in nature: soils are a mixture of different particles that can take a form of gravels, sands, silts and clays (depending on the particle size and the air and water content), mud is such a medium with a high water content.
We have set the scope of this deliverable as locomotion in low-yield environments because:

- These environments are common in mines, in particular abandoned and flooded mine, which is one of the target applications of ROBOMINERS' selectively mining robots.
- This problem definition is novel in robotics: locomotion on the solid ground is thoroughly investigated in robotics (including bio-inspired robotics). Also, underwater locomotion is well studied both from conventional and bio-inspired design perspective. However, the environments which have properties of both fluids and solids are almost entirely unexplored in robotics. Therefore, the work is this deliverable has a potential to making a higher impact also beyond the scope of ROBOMINERS.

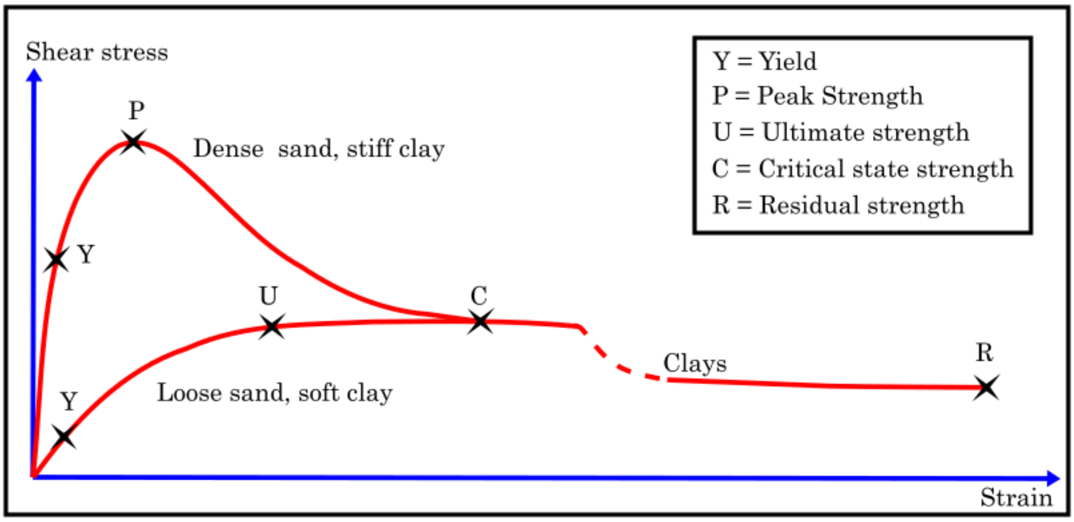

Figure 2. Typical behaviour of a low-yield environment.

2.1.2 Taxonomy of biological locomotion mechanisms in low-yield environments.

In this deliverable we conducted a systematic literature review of biology literature to identify biological principles of locomotion. The approach is described in detail in the attachment (submitted as a journal paper). The resulting taxonomy of locomotion is represented in Figure 3.

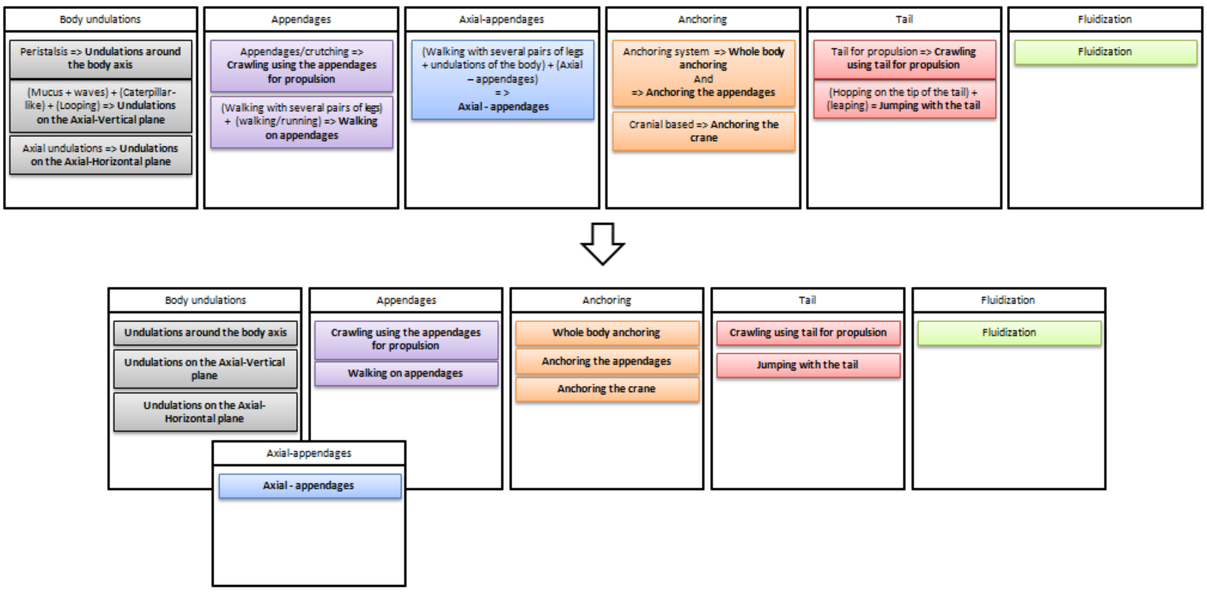

Figure 3. Taxonomy of bio-inspired locomotion in low-yield environments.

The taxonomy in Figure 3 is then classified further by identifying the physics of locomotion (again, the attached journal paper for details). As a result we identified 6 locomotion strategies that help traversing low-yield environments. These principles can be taken as starting point for ROBOMINERS robots but also in general, for robots that move in environments that exhibit both properties of solids and fluids. Also, as the physical principles are general, they can be applied for both bio-inspired and non-bio-inspired robots.

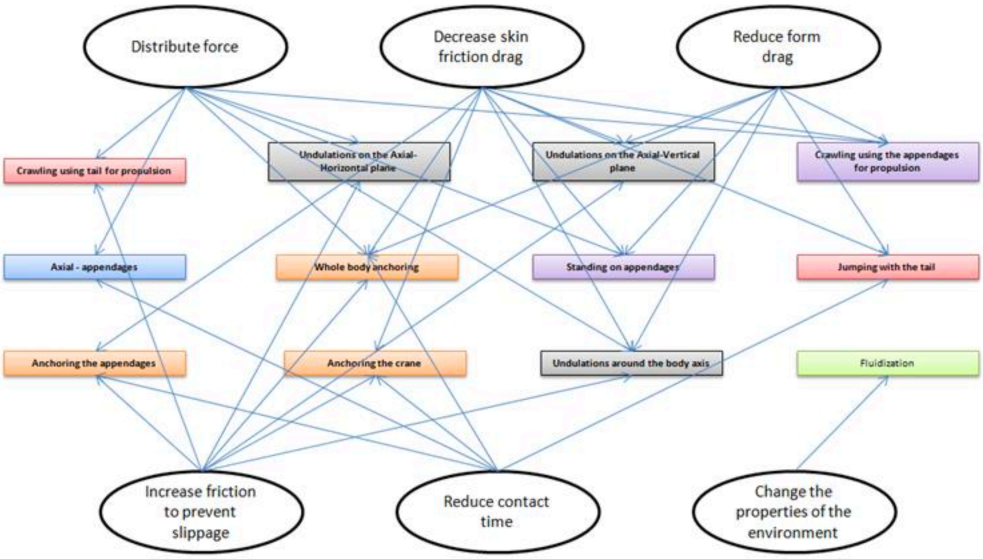

Figure 4. Taxonomy of the physical principles of locomotion.

The work carried out in this deliverable has informed the design choices in WP 3, in particular T3.1. System specifications. Table 1. shows examples of bio-inspired designs considered for the ROBOMINERS robot (discussed and developed jointly between TalTech and TAU).

Name	Beaver Robot	Conveyor worm	Whale	Centipede	Velox (from Pliant Energy Systems)	Round paws criquet
Sketch						
Ability to swim	4	1	5	3	5	2
Ability to move on solid ground	4	5	4	5	4	5
Ability to move in mud	4	4	4	3	3	3
Ability to pass a rock	2	4	3	4	1	2
Control ease	1	5	5	4	3	5
Mechanical simplicity	2	4	4	4	4	5
Resilience to failure	1	3	2	5	4	4
Energy consumption/efficiency	3	3	2	3	4	3

Table 1. Design concepts of bio-inspired robots for ROBOMINERS.

2.1.3 Legged robot locomotion strategies

In addition to the overview of biological locomotion mechanisms, we investigated the development and requirements of legged locomotion (presented at the consortium meeting in Tallinn January 2020). The summary of the overview is given in the following section.

Mobile robots in structured environments rely mostly on wheels. Indeed, wheels are one of the greatest inventions in human era, they are easy to design, manufacture, and are practical for robots that require speed. They also do not suffer from static or dynamic stability since the centre of gravity of the robot does not change when they are in motion or just standing still. Moreover, their modelling is straightforward, which simplifies the implementation of reliable control strategies. The disadvantage is that wheeled robots are not stable on uneven or rough terrains, on extremely smooth surfaces, and on slurry and muddy environments. To address this issue, using legs as a replacement for wheels has been considered. Inspired by nature, adding legs to robots was proposed as a solution for robots operating in rough terrains [1]. Legs provide a more important mobility potential than their wheeled counterparts, as they can adapt well to various environments and terrains and are highly manoeuvrable. However, this kind of mechanics require more complex control algorithms. Legs are not new to humans or animals but building legs for a robot is a complex process. Several factors need to be considered, such as controlling the robot's stability, sensing the surrounding environment, and generating appropriate motion patterns.

To tackle the stability issue, researchers defined two criteria, where at least one should be satisfied when the robot is operating: static stability and dynamic stability [2]. A statically stable robot is well balanced and does not fall over when standing. This means that its centre of gravity is within its support polygon, or ground contact base. The minimum number of ground contact points required for a statically stable robot is three. Dynamic stability is where stability is achieved by movement. Although dynamically stable robots are harder to control, they are more energy efficient and move faster than statically stable robots.

To control the robot's legs to achieve either static or dynamic stability, a dynamic model of the robot is needed. Several models have been proposed in the literature, but some depend on the number of legs. The following models are in the other hand independent from the number of legs:

- Rigid Body Dynamics (RBD): This model is the same as the one used for manipulative arms in industry robotics. Each leg is represented as a serial manipulator, and the goal is to control the articulations angle of each motor to achieve a specific configuration. This model has been heavily studied. Several advanced control schemes ensuring high accuracy and speed have been proposed. The only remaining challenge is to generate an appropriate trajectory for each leg to follow.
- Single Rigid Body Dynamics (SRBD): This is a simpler model of the robot, where the mass of the legs and their respective momentums are neglected. Only the forces and momentums that apply to the centre of mass which are generated by each leg are considered. This formulation allows to represent the robot's state fully in Cartesian space, and completely independent of the joints' angles.
- Linear Inverted Pendulum Model (LIPM): An even simpler model with a few assumptions can be deduced. If the centre of mass height is considered constant, and that its angular acceleration and velocity are zero, the non-linearity that are present in the previous models can be neglected. The advantage of this model is that it can be analytically solved, and thus having direct inverse dynamics of the robot.

Based on the above-mentioned models, several control strategies have been proposed. Basically, the idea with this model is to compensate for the dynamics of the robot (dynamic compensation using feedforward control) and add a correcting term to reach the desired joints angles. This works very well when there are no modelling errors. However, to achieve locomotion, a motion planning block needs to be added. This block would be responsible for generating where each leg should be at any given time. The first level of motion planning is gait generation. Gait generation means how each leg should behave with respect to time in order to achieve a specific trajectory. This can be walking, running, turning, etc. One method to generate a gait is to use Central Pattern Generators (CPGs). CPGs are networks of interconnected oscillators that can generate rhythmic outputs that can be used for joint trajectory planning. These CPGs can be designed by trial and error [3], by bio-mimicking [4], or with machine learning techniques [5]. Another option for control and gait generation, is to use the SRBD model as constraints and find an optimal solution directly [6]. This is called the direct method as gait generation is directly considered.

The biggest challenge, aside modelling and control for legged robots, is sensing the surrounding environment. The control of legged robots relies highly on accurate exteroceptive measurements since each leg tip needs to be precisely at a specific position to ensure its stability. Another challenge, especially for gait generation using optimization methods, is that the number of possible gaits grows with the number of legs. The number of possible events (stance and swing events for k legs) is equal to: $N=(2k-1)!$

This means that for robots with 6 legs, there are 39,916,800 possible events to explore for an optimal solution, which poses a hard constraint for robots with limited computing capabilities.

It follows from the above that having a legged robot in soft, muddy environment has its limitations. First, since in ROBOMINERS the goal is to be able to achieve locomotion in multiphase environments, the challenge for legged locomotion control is the accurate computation on the desired position of the legs, where the ground properties vary. Secondly, mud, sand and dirty water make most 3D space measurement sensors (LiDAR, cameras) hard to use, making the needed pre-knowledge for gait generation problematic. Therefore, a “synthetic bio-inspired approach” is preferred, where the ground-robot interaction is realised.

2.1.4 Conceptual shape and locomotion strategies

Following the literature overview, the possible solutions were discussed during a workshop between TalTech and TAU in October 2019, presented to the consortium during the Tallinn’s meeting in January 2020. Based on the feedback received, a concept was designed shown in Figure 5.

Out of this work, we selected the means that could at the same time answer to the challenge of locomotion in soft environments while still enabling locomotion on other environments like hard rocks. This put aside the fluidization and reduced the tail assisted possibilities because of the modularity of the robot and the potentially hard surfaces. In a desire to increase the chances of success of the locomotion principle of the ROBOMINERS, we decided to combine the advantages of the remaining principles.

Within the workshops, the solution of an Archimedean screw locomotion combined with a legged mechanism was proposed. The combination is bringing together many of the bio-inspired locomotion principles listed above. First, the large surface area of a screw mechanism is the typical feature enabling animals to reduce the pressure on the material while gaining as much traction as possible. This large surface area is provided by the screw drums. Then, when using appendages during the crawling locomotion, animals rest on a large portion of the body (here the screw surface) and push matter backward to progress forward. Similarly, when using body undulations, animals like snakes are using several portions of their body to exert pressure on the material, and the portions pushing are progressively moved backward while the front portion is periodically re-engaged into the substrate. These two behaviours are typically mimicked by the helix of the screw that pushes the material backward for any rotation of the screw (like the crawling motion) and periodically re-engages a new portion of the screw while keeping many portions still pushing the substrate.

Additionally, legs can be implemented to provide the stepping capability to avoid large obstacles, as well as the possibility to use the anchoring behaviour, i.e., extending the legs to push onto the walls of the mine enables the anchoring of the screws into the tunnel to provide anchoring points.

The combination of the screws and legs can provide a way of combining the advantages of several bio-inspired locomotion principles. An illustration of the initial concept solution can be seen in Figure 5.

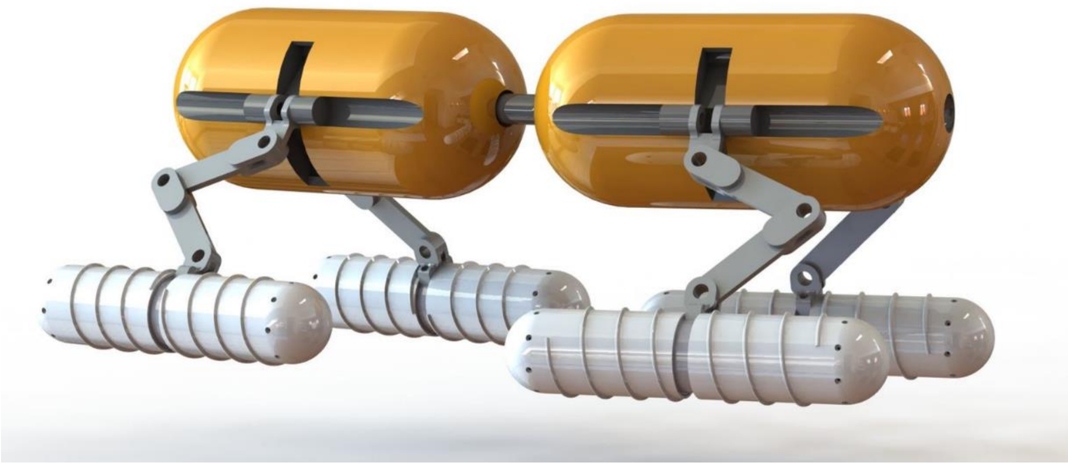

Figure 5 The screw-leg mechanism concept for ROBOMINERS

2.1.5 Conclusions

The analysis of bio-inspired locomotion in this deliverable has led to 3 different designs ideas and locomotion concepts that are currently implemented on the lab scale in hardware:

1. A general physical model for modelling and controlling the interaction of the leg with a low-yield surface. The aim is to model the stress-strain relationship of the environment from the feedback sensors of the actuator (e.g. force sensors) and control the stress (via controlling the force) applied by the foot so that the yield-point of the environment is not exceeded.
2. A shape-changing soft actuator to control the traction between the surface and the robot and to change its shape to a flapping fin when the properties of the environment change from solid to viscous or viscoelastic.
3. An Archimedean screw-propelled robot concept. Conceptually it is a conventional counterpart of flipper locomotion (exploited by mudskippers and turtles for example), where the flipper motion is simplified by actuating it with a single powered rotational joint.

3 REFERENCES

[1] H. Miura and I. Shimoyama, “Dynamic walk of a biped,” *Int. J. Rob. Res.*, vol. 3, no. 2, pp. 60–74, 1984.

[2] S. Kuindersma, F. Permenter, and R. Tedrake, “An efficiently solvable quadratic program for stabilizing dynamic locomotion,” *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 2589–2594, 2014.

[3] A. Goswami and P. Vadakkepat, *Humanoid robotics: A reference*. Springer, 2019.

[4] C. P. Santos, N. Alves, and J. C. Moreno, “Biped Locomotion Control through a Biomimetic CPG-based Controller,” *J. Intell. Robot. Syst.*, vol. 85, no. 1, pp. 47–70, Jan. 2017.

[5] J. Clune, K. O. Stanley, R. T. Pennock, and C. Ofria, “On the Performance of Indirect Encoding Across the Continuum of Regularity,” *IEEE Trans. Evol. Comput.*, vol. 15, no. 3, pp. 346–367, Jun. 2011.

[6] A. W. Winkler, C. D. Bellicoso, M. Hutter, and J. Buchli, “Gait and Trajectory Optimization for Legged Systems Through Phase-Based End-Effector Parameterization,” *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 1560–1567, Jul. 2018.

4 APPENDIX : SYSTEMATIC OVERVIEW OF LOCOMOTION IN LOW-YIELD ENVIRONMENTS

Simon Godon*, Maarja Kruusmaa*

* *Centre for Biorobotics, Tallinn University of Technology, Estonia (e-mail: simon.godon@taltech.ee, maarja.kruusmaa@taltech.ee).*

Abstract: Low-yield environments exhibit properties of both solids and fluids. For example mud, snow, soil or sand are low-yield substrates because their behaviour depends on the stress and rate of stress applied on them. Low-yield media are common in nature but very few robots are designed to move on low-yield substrates and even fewer have been demonstrated outside of the research lab. This paper surveys the existing biology and robot literature to analyse mechanical principles facilitating motion on low-yield substrates. We categorise animal locomotion on two different levels of abstraction, one preserving the biological relevance and the second, more abstract, mapping them to underlying general physical principles. We then also categorise the existing robots and some manned vehicles using the same ontologies. The result reveals which design principles are more widely used and which may represent research gaps for robotics. We also discuss that higher level of abstraction helps transferring the solutions to robotics domain also when the robot is not explicitly meant to be bio-inspired. The contribution of this paper is a catalogue of possible solutions for traversing low-yield terrains.

Keywords:
Robots, bio-inspiration, mud, locomotion, low-yield environment.

1 Introduction

The last decades have witnessed a rapid advancement of robotics applications from well-structured and defined industrial environments into an unstructed and dynamic external environment. Those robots in the real world can move on the solid ground as well as in air and in water and consequently researchers and engineers have developed terrestrial, aerial and underwater robots. However, those robots still cannot access all types of natural environments.

Low-yield environments are environments that have properties of both solids and fluids depending on how the robot is interacting with them. If a robot applies low pressure on the low-yield material, it behaves like a solid, but once the pressure exceeds the yield stress, the material behaves like a fluid. Low-yield environments are common in nature: soils are a mixture of different particles that can take a form of gravels, sands, silts and clays (depending on the particle size and the air and water content), mud is such a medium with a high water content.

Manned vehicles and some robots use wheels and tracks to move in these environments up to a limit [16]. Usually they are large and heavy enough to gain traction from the solid bottom under the loose substrate, but fail if the mud is too deep and thick. Not so many robot prototypes are addressing the challenge of traversing low-yield environments. Some quadruped [105], [9], or hexapod robots with rigid [76] or adaptable legs [77] are shown to be able to negotiate those terrains. The SeaDog robot uses spoke wheels combining some advantages of wheels and legs [68]. Undulatory robots mimicking worms [111], snakes [84] or lizards [83] is another example. Unstructured environments have also been negotiated by crawling robots such as a sea-turtle robot [86] and a mud-skipper robot [87]. A razor clam robot was designed, capable of digging through mud [137]. Some researchers designed screw-based robots, having either 2 screws [90] or 4 [81]. Recently, some robots were designed to challenge the granular lunar terrain [114] by combining wheels and walking gaits. On a different scale, sperm inspired robots have been built, moving at low Reynolds numbers [66]. For a review on robotics locomotion on heterogeneous or wet terrestrial substrates, see [2] sections 6 and 7.

Despite that there are encouraging examples how robots could be used to negotiate low-yield terrains, there are still rather few examples compared to the plethora of terrestrial vehicles for uneven terrains, aerial and underwater or even amphibian vehicles.

Yet, the locomotion problem in low-yield environments is important to solve because it would facilitate new robotic applications, for example: for search and rescue in wet forests, muddy fields, avalanches, mudslides; for the agricultural vehicles operating on wet soils (e.g. rice fields); for exploration or excavation of materials (e.g. wood, ore) with a minimal environmental impact; for environmental monitoring in high biodiversity areas (e.g. river estuaries, bogs, shores); or for extra-terrestrial exploration.

Bio-inspiration and biomimetics seems to be the most commonly used paradigm for developing robots for low-yield environments: the majority of the above listed examples claim to be inspired by animal locomotion. Typically, they mimic a specific animal or an aspect of locomotion of a specific animal.

The concept of biomimetics and bioinspiration is a specific case of a problem solving technique design-by-analogy [130] and often has its focus on biomechanics [50]. The analogy between biology and engineering can be derived at different levels but the decisive phase is the mapping from the problem domain to the solution domain using the most appropriate level of abstraction [131], [130].

However, bio-inspired design is rarely used in robotics as a systematic methodological approach and the choice of the abstraction principles is usually not explicitly or systematically discussed or justified.

In this paper we review biology research addressing the locomotion in low-yield environments and propose some general principles for designing robots for those terrains. We use abstraction on the level of general mechanical principles of the viscoplastic medium to derive engineering goals. We also categorise the existing robotic research and demonstrate that some of those principles have been explicitly or implicitly already used in robots or other vehicles and since they are sufficiently general, the resultant design does not necessarily need to be explicitly bio-inspired. The motivation of this overview is to offer a systematic approach, general guidelines and design targets for developing better vehicles in low-yield environments.

2 Background: soil mechanics

The soil is a complex substrate made up of four components: minerals, air, water and organic matter. These components can be present in varying proportions depending on precipitations, proximity to water bodies or compression of the material. Depending on the minerals' particle size, the soils can be classified as clay (smallest), silt, sand and gravel (largest). Soil behaviour depends on the water content; when the water content is very high, the soil behaves as a fluid, when it decreases the mud behaves as a plastic or viscoplastic, and it is solid when the water content is low [11]. The plastic behaviour means that above a certain stress, called yield stress, the material does not return to its original shape. The smaller the particles, the lower the permeability to water and the more prominent is the plastic behaviour. Viscoplastic behaviour exhibits properties of both solids and fluids, and material deformation depends also on the rate of stress [23], [10]. The typical stress-strain curve of soils is shown in figure 1.

Hence, moving in mud means dealing with a material constantly changing its state between solid and fluid. For not sinking into the mud, the robots or animals have to apply a pressure lower than the yield stress. In case it is already submerged, the animal or robot has to deal with moving in a viscoplastic material, where both stress and stress rate play a role.

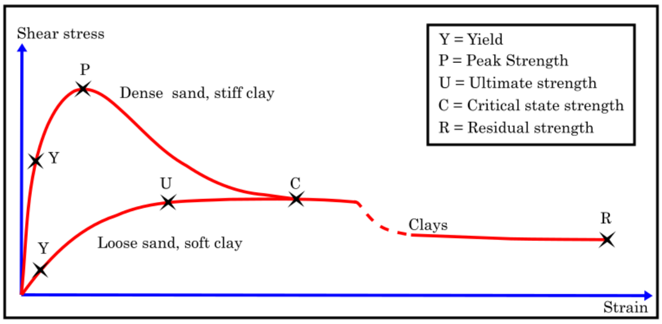

Figure 1. Typical stress-strain curve of soils, sketched according to [11]. The difference between the two curves lies in the volume change: if a soil is loose or soft it will dilate directly and the shear stress will rise. If it is already compact, its shear-stress will increase more due to the dilatancy of mineral grains until the bonds break and the curve meets the loose/soft curve. In both cases, if the particles are small, a residual strength exists after the critical state, which enables the muds to resist pressure.

3 Methods

This paper aims at answering the following questions:

-What type of locomotion modes and mechanisms are present in nature for locomotion in low-yield environments?

-How to classify those modes and mechanisms of locomotion in low-yield environments?

-What are the underlying physical principles enabling locomotion in low-yield environments?

-Do those modes and mechanisms share any common physical principles that are abstract enough to be applied to robots including non bio-inspired robots?

To answer those questions, we conducted a review of biology research, focusing on animal locomotion in low-yield environments. We identified relevant research papers and categorised them based on locomotion mechanisms and patterns. Finally, for each category, we tried to identify the underlying mechanical principles for motion in low-yield environments. We have also mapped the existing robots into the presented categories showing that successfully developed solutions implicitly or explicitly are designed against those principles and suggesting that defining those principles as design targets will help to faster and easier develop better vehicles.

3.1 Identifying locomotion principles

The first methodological step is described in detail in Appendix A. It is a systematic review of biology literature addressing locomotion in low-yield environments. From this overview we could identify sixteen different ways of locomotion, summarised in figure 2.

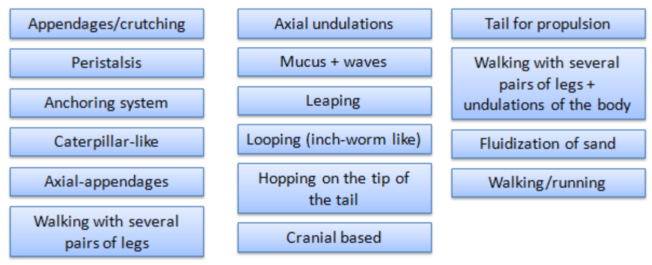

Figure 2. Locomotion principles identified from the literature review.

Those locomotion mechanisms were further on clustered based on their similarities. As a result, we derived 6 classes represented in figure 3, upper row, which we then regrouped under more generic sub-categories. This led to the final classification, presented in the lower row of figure 3. Any specific animal described in literature could use more than one of those principles:

1. Body undulations
2. Appendages
3. Axial-appendages
4. Anchoring
5. Tail
6. Fluidization

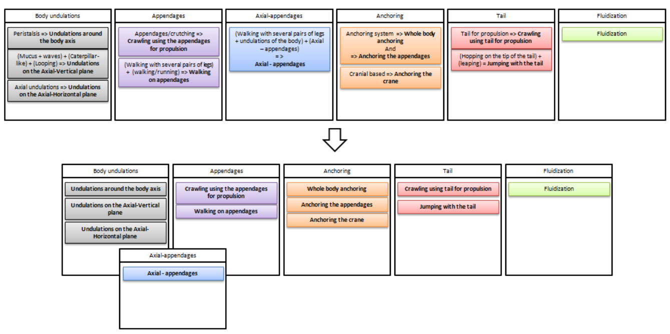

Figure 3. Final categorisation of the locomotion principles after regrouping and merging the initial categories.

In the next sections, each of the six classes will more closely described with the emphasis on the mechanics of soils and with references to the possible robotic analogues.

4 Locomotion principles in low-yield environments

4.1 Body undulations

This principle lies on the undulation of the animal body along its anteroposterior axis. By doing so, the animal pushes against the ground with some of his body parts while moving the rest forward. Then, the parts alternate their role in an undulation pattern. In some cases the body pushes and advances at the same time. Undulations have been observed to occur in three different geometries; in the Axial-Horizontal plane (AH), in the Axial-Vertical plane (AV) or along the anteroposterior axis (see figure 4).

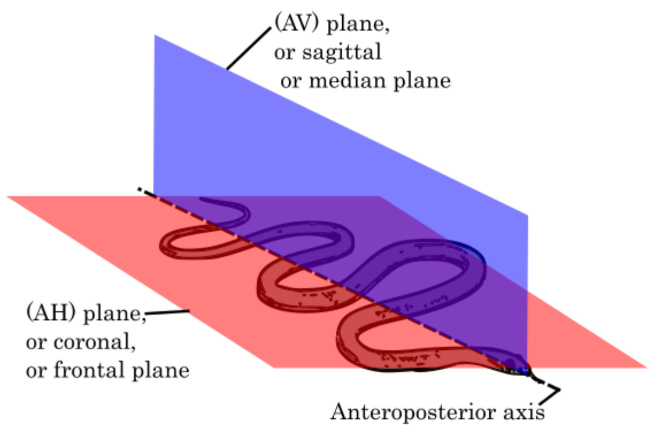

Figure 4. Representation of the Axial-Vertical plane in blue (AV, also called sagittal or median plane in anatomy) and the Axial-Horizontal plane (AH, also called coronal or frontal plane) in red. The line joining the head and the tail (dashed line) is the anteroposterior axis.

4.1.1 Axial-Horizontal undulations

This type of movement consists in undulating the body on the AH plane (red in figure 4) so that several points of the body push against the soil simultaneously while advancing the body forward. Doing this, the efforts are distributed along the body allowing for a small amount of force to be applied at each location, thus reducing the pressure on the ground. This is of particular interest in an environment which may flow ever under a small pressure such as mud or sand. The well known animal using this locomotion pattern is snake [132]. Limbless tetrapods such as snakes are described to generally move in four different ways (Undulation, concertina, sidewinding and rectilinear). Among them, the first one, undulations, consist of producing continuous Axial-Horizontal movements (see figure 5).

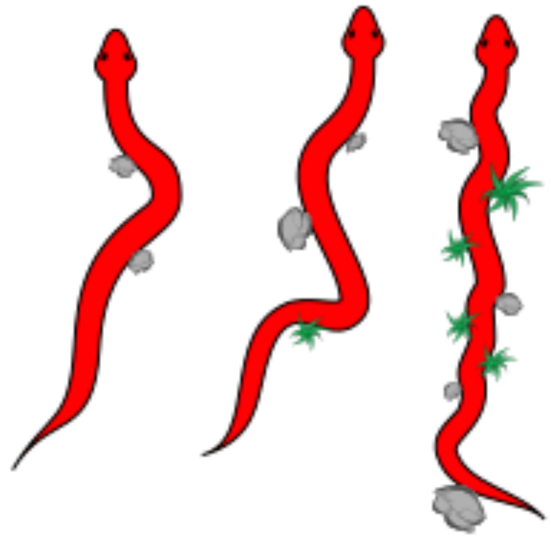

Figure 5. The Axial-Horizontal undulations by snakes, according to [132]. The grass and rocks are examples of objects the snake can push against.

Limbless tetrapods produce a wave of contraction of their lateral muscles propagating from the front to the back to bend the body sideways. Then the next phase-shifted wave produces bending in the opposite direction. The alternating undulations create contact surfaces distributed along the body that push against the soil. The ground reaction forces have a forward and a sideways component, the sideways components counteracting each other while the forward component pushes the body forward. This locomotion strategy produces skin friction drag, which can be reduced by scales, mucus or by lifting some body sections.

The second locomotion strategy, used only by snakes, is the sidewinding [132], in which the body has two sections in contact with the ground and two lifted off the substrate. This means that pressure on the surfaces is higher with only two contact areas, and this deforms the ground so that the snake produces a heap of soil against which it pushes itself forward. This particularity makes this method well suited for low-yield environments as they easily deform under pressure. A sidewinding snake robot has been designed to study this pattern [84]. The lungfish also uses AH undulations when swimming in a viscous solution, such as mud with high water content [60]. This type of undulations is also used by some worms to go through muddy sediments [33]. Two main progression techniques are used by worms, consisting in either fracturing the sediments or reorganising the sediments while using undulatory motion [33]. Such undulations are also used by burrowing eels [58] and sandlances [48] to burrow into the sea bottom, and by a diversity of desert reptiles, like the sandfish lizard which swims below the desert surface using undulatory movements [51]. A sandfish lizard robot has been designed to mimic this pattern [83].

4.1.2 Axial-Vertical undulations

The second type of undulation is produced on the Axial-Vertical plane, shown in blue in figure 4. In this mode of locomotion, the body alternates between a resting phase and an active phase consisting of oscillations. This pattern is used by for example seals [93]. Seals are described to use a locomotion pattern in which they bend their back while putting their weight on the front part of their body. This brings the posterior part of their body forward. Then, they apply force on the ground with the posterior part of their body while straightening their back and supporting the movement with a stroke of the flippers. This moves the anterior part of the body forward. This pattern is used by seals on rocky or sandy areas, demonstrating its effectiveness in unstructured environments. The same pattern is used by inch-worms [100], leeches [37] and caterpillars [122]. An illustration of this locomotion can be observed in figure 6.

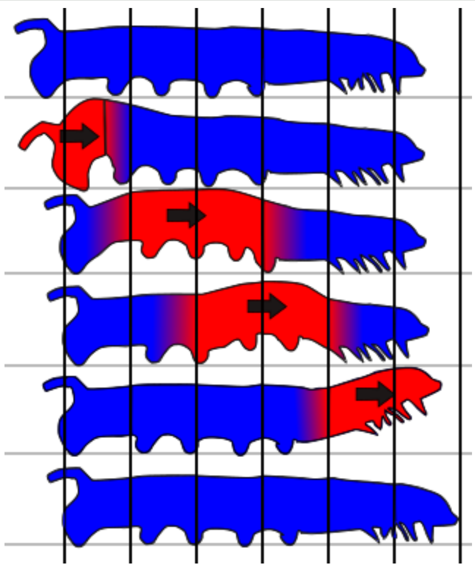

Figure 6. A movement cycle of the caterpillar. The forward moving parts are highlighted in red and the static parts in blue.

Similarly to seals, caterpillars alternately bend each of their body segments, but contrary to seals, support to the ground with legs instead of pushing against it with the surface of their trunk. Different molluscs, such as snails and slugs, also use these undulations to move forward [124]. Here, the differences mainly lie in that they produce mucus to reduce friction and backsliding, or in that they have a specialised foot producing complex undulatory waves. This specialised foot can produce sideways and concentric waves enabling the mollusc to move diagonally or turn on the spot. Limbless tetrapods also use AV undulations as one of their four locomotion strategies [132]. In this strategy, they alternately move their ventral portions forward, similarly to a snail's foot, while the body stays straight.

Apart from AH undulations, AV undulations use a different orientation of the waves of undulations which in turn implies that there is no drag on the substrate because the parts of the body moving forward are lifted up. The other difference between AH and AV undulations is that with AV undulations, each section of the body alternates between stance and forward phase, while the entire body moves simultaneously with AH oscillations.

4.1.3 Undulations around the body axis (peristalsis)

The third type of undulation-based locomotion consists of undulations at the intersection of the AH and AV planes: around the anteroposterior axis, represented as a dashed line in figure 4. This undulation is called peristalsis. One or several waves shorten or lengthen the body segments. While a body segment is shortening, it widens and grips the soil more firmly to serve as an anchor point from which the next segment is pulled [33]. An illustration of a worm moving with peristalsis can be seen in figure 7. To grip the soil more firmly, some worms also have chaetae

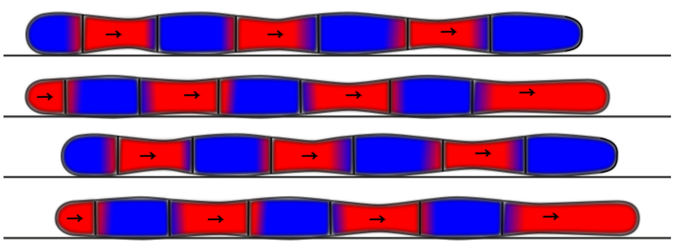

Figure 7. A worm using a peristaltic motion. The red parts are making forward progress while the blue ones are anchored to the soil.

on their segments which protract during the stance phase to increase friction and retract during the forward movement [45]. The peristaltic waves end with the enlarging of the tip of the front end of the worm, which when underground acts as a wedge to crack the soil [53]. This wedge appears to reduce the form drag by reducing the frontal area of the worm.

Similarly to AV and AH undulations, peristaltic waves push against the ground on several points, distributing the forces and reducing the pressure on the soil. However only with AH undulations, the entire body progresses at the same time and slides on the ground, requiring anti-friction mechanisms. With AV undulations, the advancing parts are lifted off the ground while with the peristaltic motion, they are shrunk while remaining aligned with the body axis. In both cases, the surface friction is consequently reduced. However, form drag is only reduced with the peristaltic motion as the worm shrinks and expands its frontal area.

4.2 Use of appendages

In low-yield environments, appendages (e.g. legs, fins, flippers) can be used for walking or propelling the body forward while lying on the trunk.

4.2.1 Walking on appendages

Most of the terrestrial mammals, birds and insects use appendages for walking. If the low-yield environment cannot carry the animal's body weight, then animals with long legs can reach the solid bottom and walk on it. This strategy can only be used when the layer of mud is not too deep. The second strategy implies reducing the pressure exerted by feet to not exceed the yield of soil. This strategy can be applied either by increasing the number of legs to distribute the body weight, this is the case for arthropods (e.g. crabs, centipedes); or by increasing the surface area of feet, this is the case for animals with very long fingers or webs (e.g. lizards, ducks, beavers).

The only studies found in the literature about the first strategy are studying cows in slurry or sand. Cows have thin elongated legs with a hard hoof enabling them to penetrate through the substrate and reach the hard bottom. They reduce their stride frequency because it is difficult to penetrate and retract the leg through the slurry. They also increase their stride length because the risk of slip is reduced when the animal has a strong foothold on the solid surface under the slurry [98]. The same increase of stride length was observed when walking in sand [118]. The Bigdog robot uses this locomotion principle to walk in mud and snow [105].

Many species distribute their body weight over a larger number of appendages. This is the case for arthropods (segmented animals) which possess six to hundreds of appendages [45], [57]. Centipedes provide an example of those. Their legs can be moved in different combinations giving rise to a wide variety of locomotion patterns, sometimes coordinating these movements with body undulations [124]. The light highly distributed weight enables these animals to walk on very soft substrates. Different species of crab are also living in muddy or sandy environments using 8 of their 10 legs for locomotion [42]. Again, the underlying physical principle here is the partition of the body weight on several legs, reducing the pressure on the substrate. The AmphiHex [77] and RHex [76] robots are using this principle.

Webbed feet are often used by amphibious animals such as salamanders or animals living in wet environments such as ducks or beavers. Their webbed feet increase the contact area with the ground. Salamanders have also developed a gait which always keeps 3 legs in contact with a flowable substrate [8] to stay below the yield stress. Some lizards increase their contact area using long fingers. The basilik lizard for example has been observed to balance and avoid sinking into a flowable substrate by reducing its stride length as the surface hardness diminishes [9]. The Basilikbot was designed to study the effects of substrates properties on the locomotion parameters [9].

Hatching turtles use alternating sequences of strokes ({left fore-flipper + right back-flipper} and {right front-flipper + left back-flipper}) when they move rapidly on sand [85] (see figure 8). These turtles also bend their wrist

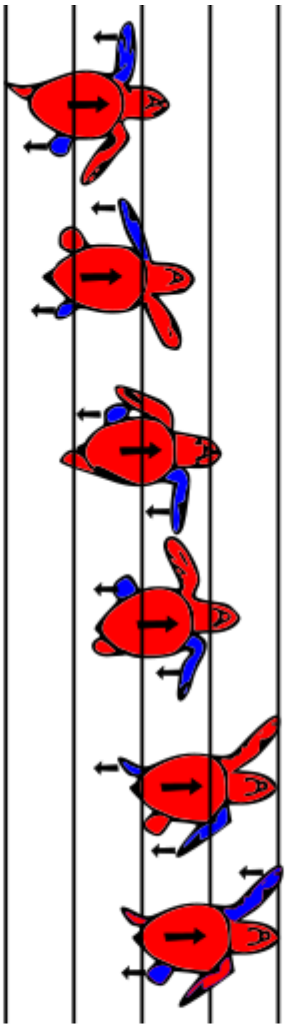

Figure 8. The stepping pattern of a quickly moving hatching turtle using only its four appendages. The blue parts are the flippers supporting against the ground while the red parts are moving forward. Drawn according to [85].

while moving forward to keep the flat surface of their flipper orthogonal to the force vector, increasing the effective contact area with the substrate.

Moles have two specialised arms for burrowing but they can also use them for walking on their long and thin edges. The rear feet are also long and thin, and are used to push the mole forward [139]. The mole cricket has a similar anatomy and a similar locomotion pattern [142].

4.2.2 Crawling using appendages only for propulsion

Some other animals rest on the substrate with a large portion of their body to prevent sinking. They move forward with backward strokes of their appendages and reduce the drag by lifting the body off the ground. The well known example of this locomotion principle is the mud-skipper [128], [95], [56]. This fish uses an alternating pattern of 3 supporting points ({left pectoral fin, right pectoral fin, tail} and { left pelvic fin, right pelvic fin, tail}). See figure 9.

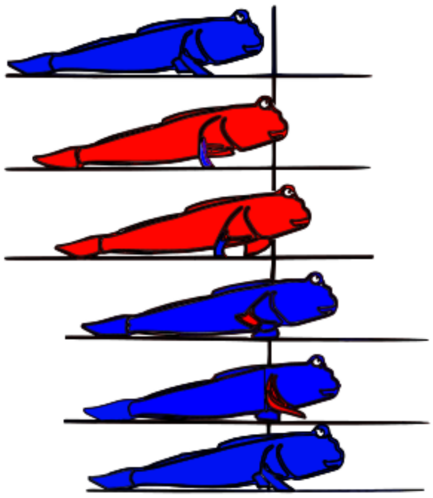

Figure 9. Locomotion pattern of the mud-skipper using the alternating tripod system. The red parts are moving forward while the blue ones are not. Drawn based on [56].

When in resting position, the mud-skipper touches the ground with its large pelvic fins and the tail. Before moving forward, it swings its pectoral fins forward until they touch the ground. It then pushes the soil backward with its pectoral fins while retracting its pelvic fins. In the end of the stroke, the mud-skipper lifts the pectoral fins off the ground and stands on its pelvic fins, again in resting position and ready for another cycle. A similar pattern is used by marine turtles on land. These turtles are resting on their shell and move forward by producing a backward/downward stroke with all 4 fins at the same time, simultaneously lifting their shell off the ground to reduce drag [85]. A sea-turtle inspired robot using some features of this locomotion pattern was built [86].

4.3 Body undulations + appendages

Fish are moving in water using axial undulations. They developed limbs to invade land [5] ending up with locomotion strategies mixing axial body movements and limbs. The axial-appendages locomotion pattern is described as one of the three modes of locomotion of fish on land [95]. This mechanism consists of anchoring a pectoral fin into the substrate and bending the tail towards the other side of the body. Fish then quickly straighten the tail, propelling the body forward by rotating around the anchored fin. They then repeat the cycle with the opposite pectoral fin and bend the tail to the other side. This locomotion pattern is typical for walking catfish *Clarias* [64] (see figure 10).

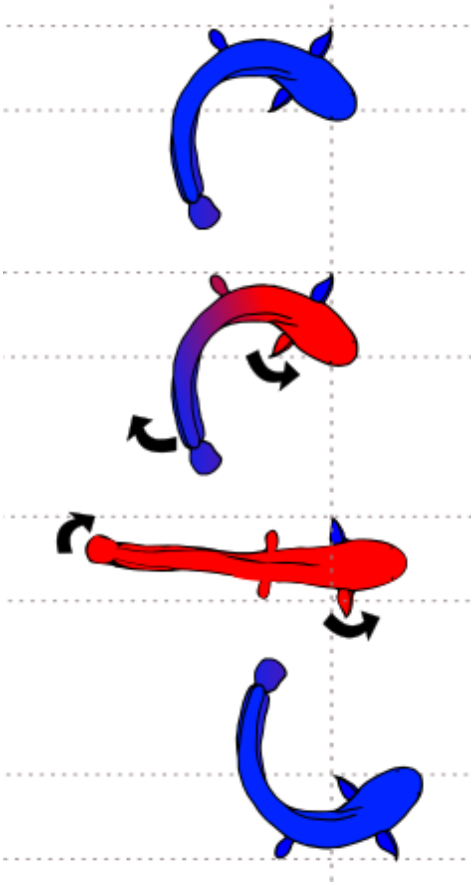

Figure 10. Locomotion of the *Clarias* on land according to [64]. The red parts are making forward progress while the blue parts are pushing against the ground or are static.

Lungfish use a combination of axial undulations with its fins to walk on the bottom of water-bodies. Its locomotion pattern is adjusted to the viscosity of the medium. The more viscous the medium is, the less it uses its limbs [60].

Some tetrapods, such as salamanders, use the retraction and rotation of appendages in combination with AH undulations of the girdle when moving on land [38]. A similar pattern is used by lizard species such as the sandfish lizard, which uses appendages and body undulations to burrow into sand [82].

Polypterus senegalus uses two gaits depending on the substrate complexity [115]. If the substrate is uneven so that the fish can push against stones or lumps, it uses mainly AH undulations because the body surface (bent in an S-shape) provides enough support against the elements of the environment. The smoother is the terrain, the more the fish walks on its fins coordinating their motion with AH undulations while lifting the anterior part of the body so that it reduces friction drag with the soil.

Climbing perch also uses undulations in combination with appendages to move on land. However a usage of its detachable sub-opercular to anchor on the ground makes its locomotion different from other tetrapods and fish (see next section) [27]. This fish exploits its pectoral fin to help rolling its body towards the side of the sub-opercular and then pushes its body forward over the anchored sub-opercular with a tail stroke, sometimes with a little additional stroke with the pectoral fins. Seals also use a similar gait (their rapid gait) by bending the body to one side before pushing simultaneously with the tail from one side and with the flipper from the opposite side [93].

Some multi-legged animals, such as centipedes use their legs in a peristaltic-like pattern. This creates high concentration of appendages pushing on the substratum [70], [45]. The polychaete *Nereis virens* also uses body AH undulations from the back to the front in combination with a rowing pattern of the legs [71]. A Nereis robot was created to explore this locomotion pattern [111]. Different terrestrial worms also use peristalsis along with appendages to facilitate anchoring. These appendages are retracted to reduce friction with the tunnel walls during movement [33].

In most cases animals using axial-appendages locomotion have adopted AH plane undulations while also propelling themselves with side appendages to lift the body off the substrate. They negotiate the low-yield substrates by resting on the trunk (distribute body weight) while the appendages and undulations serve to provide high instantaneous power.

4.4 Anchoring

The fourth method of locomotion relies on anchors to push or pull on them and advance the rest of the body. Some animals alternately use several anchors while others use only the head as an anchor.

4.4.1 Full body based

The first category of animals uses the entire body as an anchor, alternating between regions of the body. The typical animal using this method is clam. The locomotion cycle of a clam can be observed in figure 11.

Clams use a dual-anchor in which the foot and the shell alternately play the role of an anchor. They first widen

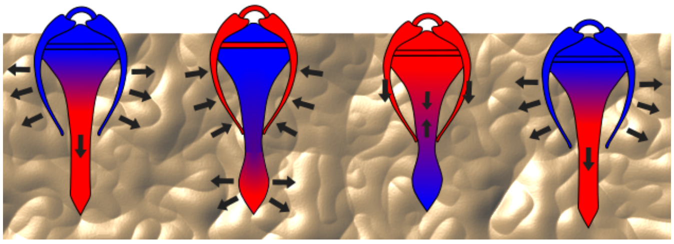

Figure 11. Locomotion cycle of a clam. The moving parts are specified with red color and the static ones with blue. Schematics is based on [30] and [124].

their shell to hold grip on substratum, preventing the shell from sliding. Then, they penetrate through the substrate expanding their thin foot. Next, they invert the roles of the foot and the shell: they widen the foot and close their shell to get a better grip with the foot and loosen the grip with the shell. Finally, they pull their shell forward by retracting the foot into the shell, completing the cycle [138], [124]. The RoboClam has been created to mimic the Razor Clam locomotion [137].

Snakes also use an anchoring mechanism when moving with concertina locomotion [132] (see figure 12). When adopting this locomotion, the snake bends a part of its body into an S-shape to increase the friction with the ground and advances the rest of its body relative to this anchor. The parts of the body in front of the anchor straighten and move out of the S-shape portion while the parts of the body behind the anchor bend to constitute a new anchor. Following this pattern, the anchor progresses from the front to the back of the snake, and the body moves forward section by section.

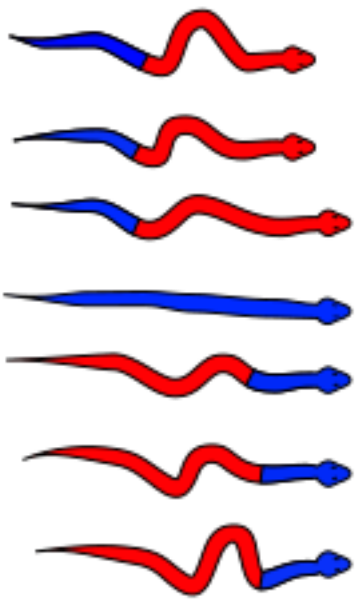

Figure 12. The concertina locomotion of snake, according to [132]. The red parts are the moving parts while the blue ones are fixed on the soil.

4.4.2 Cranial based

The second strategy is based on anchoring the head. This is the case for the lungfish which, when on land, anchors its head into the soil and moves the rest of the body forward by bending it to the side. It then pushes its tail against the ground while straightening its entire body, propelling the head forward to anchor it further into the substrate and start another cycle [60], [95], see figure 13.

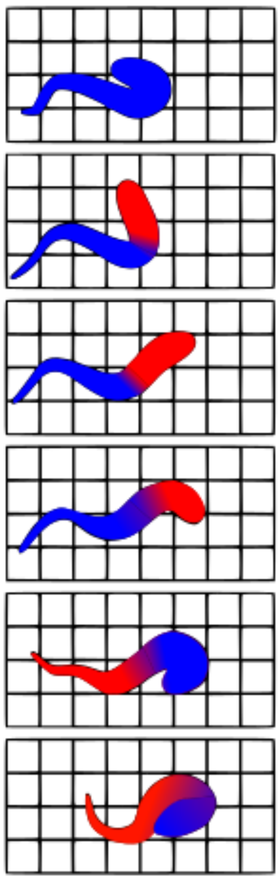

Figure 13. Representation of the locomotion pattern of the lungfish on land. The red parts are making forward progress while the blue ones are pushing/pulling on the soil. Drawn according to [60].

A similar gait is used by climbing perch on land [27]. The particularity of the climbing perch is that its sub-opercular is able to move relative to their opercular. This sub-opercular is used as an anchor as well as a grapple hook to climb obstacles.

4.4.3 Anchoring the appendages

This third anchoring method is using appendages to attach to the ground and uses the tail to propel the body over the anchor. An animal using this method is the *Clarias* [64]. See figure 10.

The general physical principle behind the variations of anchoring based locomotion is that it relies on sequences of yielding the substrate when getting a grip and staying below the yield point when moving forward. This often implies shrinking or widening body parts to increase or reduce the surface area hence negotiating the yield stress.

4.5 Tail

Two strategies exist for tail-based locomotion in low-yield environments. The first involves crawling on the soil while the strokes of the tail facilitate the forward motion. The second strategy utilises the tail for jumping.

4.5.1 Crawling with the tail

Mud-skipper is an example of animal using the first strategy as it adopts its tail when climbing an incline. It uses its tail more and more frequently to jump forward as the incline steepness increases [87]. Moreover, this mechanism also prevents back slippage when the tail is anchored to the ground. This mechanism can be observed in figure 14. A mud-skipper robot has been designed to study this feature [87].

Lungfish also use their tail to move forward in all of their three locomotion strategies [60]. They change their locomotion strategies based on the viscosity and density of the medium: the range of undulations increases with the viscosity of the fluid. When the medium becomes sufficiently thick to provide an anchoring point, they anchor their fin to the soil and give powerful strokes with the tail. Climbing perch also use a similar locomotion strategy in mud [27].

An arthropod such as *Nebalia bipes* also uses the tail for propulsion. While digging into the sand with its legs, it propels itself forward with tail strokes [129].

Finally, sperms use the tail (flagella) while moving in low Reynolds number environments. The flagella oscillates from side to side bending in a chiral shape to break the symmetry and enable propulsion [47]. A sperm inspired robot was built on this model [66].

4.5.2 Jumping with the tail

The terrestrial blennies (animals similar to the mud-skippers) are also able to move on land by jumping on their tail [61]. These blennies touch the ground with the lateral part of their tail which is much wider than the ventral surface of the tail. This enables them to increase traction and perform powerful jumps. To facilitate jumping, they bend their body into a C-shape (bringing the tail close to the head), well know to be used by fish to trigger energetic starts (C-starts).

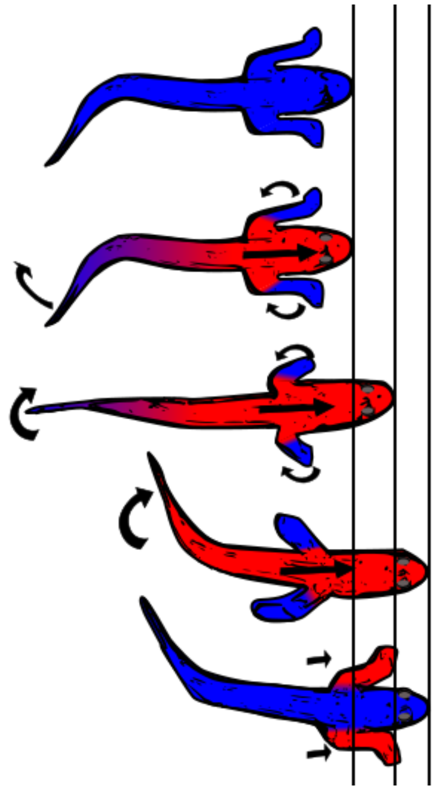

Figure 14. The mud-skipper using its tail to help the crawling movement. The red parts are making forward movement while the blue ones are static or pushing/pulling on the soil. Drawn after [87].

The nematode *theristus caudasaliens* hops using the posterior part of its body. It stores elastic energy by slowly bending the back end and then quickly releases it, triggering a jump [1]. See figure 15.

Generally, tails are used in mud to generate powerful strokes and not for a continuous motion. This strategy is often used in combination with the body lying on the soil and keeping the pressure below the yield point. The dynamic effects of these powerful strokes into the low-yield soils do not appear to be studied. It can be speculated however, that the property of viscoplastic materials to delay and distribute impact helps the animal to push off the ground before the matter yields.

4.6 Fluidization

Fluidization implies moving sand or any granular medium fast enough to suspend the particles and thus

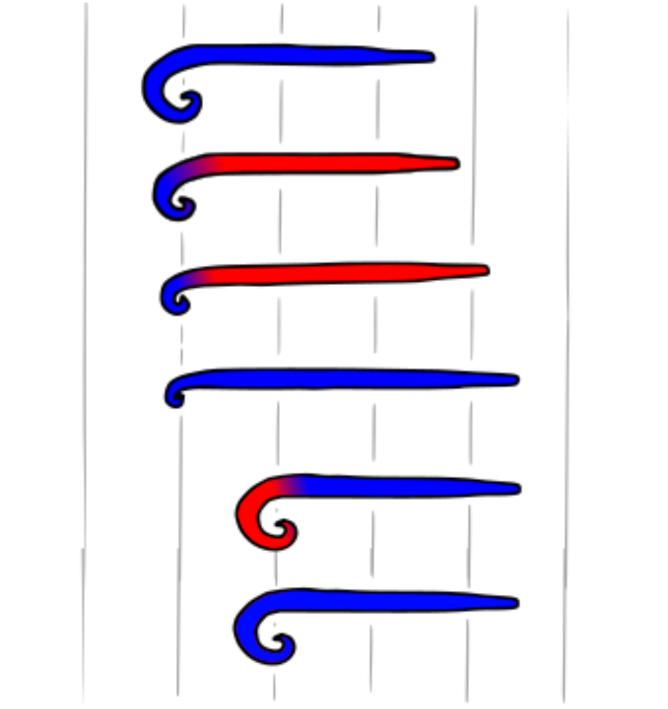

Figure 15. The hopping pattern of *theristus caudasaliens*. The red parts are moving forward while the blue ones are not. Drawn after [1].

make the granular medium behave as a fluid. This reduces friction and helps the animal to move forward.

Sandfish lizard is described as swimming into the sand, because its rapid oscillations fluidize the sand [51]. Razor clam has also been observed to use this principle to reduce friction of its shell when anchoring, thus facilitating the penetration of the body into the sand [138]. The RoboClam uses this principle to dig itself through the ground [137]. Some worms have also been described to use this principle [33].

5 Underlying physical principles for locomotion in low-yield environments

The locomotion mechanisms described in previous sections often share common physical principles that facilitate the animal to negotiate low-yield terrains. Those, more abstract principles can be used by animals regardless of their anatomy or locomotion pattern and are therefore common to many species. We have identified six general physical principles: the animals can distribute force, reduce skin friction drag, reduce form drag, increase friction to prevent slippage, reduce contact time, or change the properties of the environment. The relations of those principles to locomotion mechanisms are represented in figure 16.

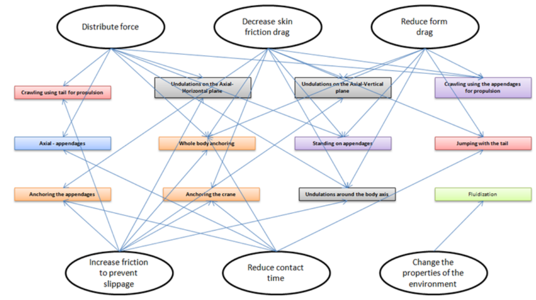

Figure 16. The physical principles used by animals to move in low-yield environments.

A very common strategy used by diverse animals is to distribute force for keeping the pressure exerted to the soil below the yield point. The animals take advantage of large surface areas, either by resting on their trunk, by increasing the number of appendages or widening distal parts.

Decreasing skin friction drag also facilitates the movement in low-yield environments and there are diverse mechanism for achieving it. The friction drag can be reduced by lifting or shrinking the moving parts off the medium, by jumping off the medium but also by lubrication or usage of low-friction material couples.

When some parts of the body are submerged by the substrate, form drag can be reduced by lifting or shrinking the moving parts off the medium or by jumping.

The fourth common principle is to prevent backslippage. Many locomotion mechanisms result to increasing friction on the static parts. Friction can be increased by anchoring body parts, increasing the contact area, bumping the weight over the contact surfaces, deforming the soil or relying on its roughness.

The fifth common principle is using viscosity of low-yield environments as an asset. Animals reduce the contact time with the substrate by increasing their speed. The viscoplastic materials answer to a faster solicitation with a higher shear stress, hence allowing higher pressures to be exerted on them.

Finally, some animals fluidize the environment to facilitate the progression. This reduces drag and enables using locomotion strategies otherwise used when swimming.

5.1 Locomotion principles used by robots

Some locomotion principles appear already to be used in existing robot prototypes. Similarly to the biology review, we have identified those principles and found analogies with animals. Sometimes the biological principle used by robots is explicitly stated in the papers and sometimes we have ourselves mapped the robot to the possible closest biological analogy. When analysing figure 17, it appears that walking and AH undulating seem to be widely explored locomotion principles used by robots. Few robots have been demonstrated to move in such substrates using fluidization, axial-appendages locomotion, AH undulations, tail for crawling or whole body anchoring. No robot, to our knowledge, has been developed for low-yield environments using either the appendages as an anchor, undulations around the body axis or in the AV plane, nor the appendages or the crane as anchors. This points towards possible research gaps and underexploited opportunities.

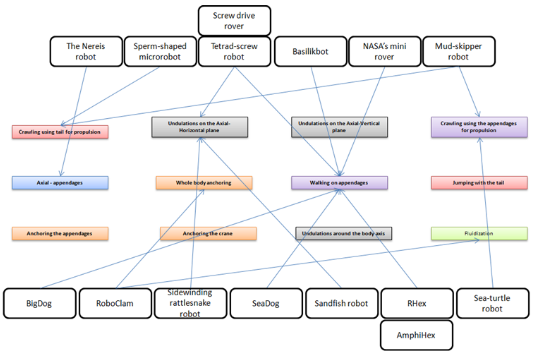

Figure 17. The bio-inspired modes of locomotion used by robots: The Nereis robot [111], Sperm-shaped robot [66], Screw-drive rover [90], Tetrad-screw robot [81], Basilikbot [9], NASA's mini rover [114], Mud-skipper robot [87], BigDog [105], RoboClam [137], Sidewinding rattlesnake robot [84], SeaDog [68], Sandfish robot [83], RHex [76], AmphiHex [77], Sea-turte robot [86].

Similarly, the existing robots can be mapped to abstracted physical principles by investigating their design and mechanics of locomotion. This mapping is proposed in figure 18.

Analysing figure 18 reveals that a majority of robots were designed to distribute force, prevent slippage or reduce form and friction drag. However, reducing the contact time or changing the properties of the environment seem to be mostly unexplored. Note that not all the robots analysed in figure 18 are explicitly bio-inspired. Indeed, principles such as force distribution or increasing friction an also be achieve by other design approaches, e.g. fat tires, tracks, screws etc. Several manned vehicles can be found already exploiting those solutions. Examples of such wheeled vehicles include the Sherp ATV [113], the Burlak [92], the Frontier 750 scout [6]. Tracked vehicles, such as the Ripsaw tank [108], the Tinger track [120], the Bvs10 beowulf [116] are designed to increase friction and distribute weight. Screw-propelled vehicles have been proposed, built and proven reliable in muddy and sandy surfaces (the MudMaster [97], the ZIL-2906 [145], the Riverine Utility Aircraft [40]).

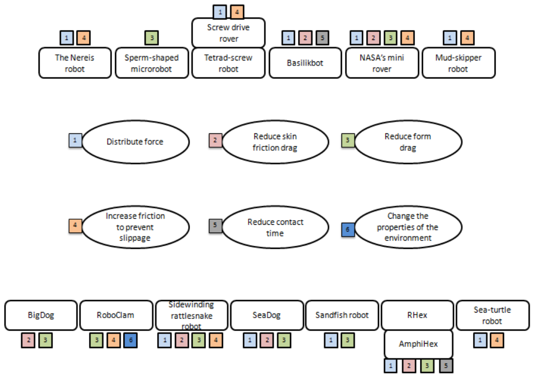

Figure 18. The general physical principles used by robots in low-yield environments. The robots references: the Nereis robot [111], Sperm-shaped robot [66], Screw-drive rover [90], Tetrad-screw robot [81], Basilikbot [9], NASA's mini rover [114], Mud-skipper robot [87], BigDog [105], RoboClam [137], Sidewinding rattlesnake robot [84], SeaDog [68], Sandfish robot [83], RHex [76], AmphiHex [77], Sea-turte robot [86].

6 Discussion

The contribution of this paper is a systematic review of biology literature for identifying locomotion principles that can be applied for robot design in low-yield environments. The principles are identified at two different levels of abstraction: one preserving the biological relevance and the other abstracting it away to form more general underlying principles for locomotion mechanics. The higher level of abstraction also allows expanding the ontology to non bio-inspired robots. It is perhaps worth mentioning that using abstract language and non-technical terms to describe a problem is a well-know technique of systematic problem solving proposed to avoid tunnel vision and early fixation [4]. In the current case, for solving the problem of motion in low-yield environments, it may help the designer to propose more diverse solutions.

The results described in this paper have several shortcomings and limitations. First of all, we observed that biological literature strictly addressing the biomechanics of low-yield environments is very scarce, especially when compared to the papers generally addressing legged locomotion, flying biomechanics, swimming biomechanics etc. Even from the identified papers, the focus of the paper was often on some other aspects (e.g. the behaviour of the animal) and biomechanics was only very briefly described. And even if the focus was on biolocomotion the papers used the terminology and methods of biology, rather than physics and mechanics, e.g the locomotion mechanisms where descriptive and not mathematically formulated or the physical quantities not measured. Therefore our derivation of the physical principles is purely hypothetical and definitely different mappings from the ones presented in this paper can be developed. In some cases our interpretations of the physical principles are purely speculative. For example, the effect of timing and duration of stress to the viscoplastic environment was not described or analysed anywhere in literature.

The applicability of the identified principles is also not necessarily straightforward with the current technology and materials. For example, deforming the animal body to re-distribute stress is much more complex to mimic than statically enlarging surface area (e.g. wider feet or tires). From an applicability point of view, a special concern is allometric scaling. If the length of an animal/device increases linearly, its body weight increases in the cube but the surface area supporting it only increases in square (and hence the pressure increases linearly with length), making it difficult for bigger animals (or vehicles or robots) to stay below the yield stress of the soil. Therefore not all the bio-inspired solutions are necessarily feasible when replicated on robots.

This research has been supported by project ROBOMINERS which received funding from the European Commission's Horizon 2020 research and innovation programme under grant agreement No. 820971

References

[1] Priscilla JM Adams and Seth Tyler. Hopping locomotion in a nematode: Functional anatomy of the caudal gland apparatus of theristus caudasaliens sp. n. *Journal of Morphology*, 164(3):265–285, 1980.

[2] Jeffrey Aguilar, Tingnan Zhang, Feifei Qian, Mark Kingsbury, Benjamin McInroe, Nicole Mazouchova, Chen Li, Ryan Maladen, Chaohui Gong, Matt Travers, et al. A review on locomotion robophysics: the study of movement at the intersection of robotics, soft matter and dynamical systems. *Reports on Progress in Physics*, 79(11):110001, 2016.

[3] Brett R Aiello, Heather M King, and Melina E Hale. Functional subdivision of fin protractor and retractor muscles underlies pelvic fin walking in the african lungfish protopterus annectens. *Journal of Experimental Biology*, 217(19):3474–3482, 2014.

[4] Genrikh Saulovich Altshuller. *The innovation algorithm: TRIZ, systematic innovation and technical creativity.* Technical innovation center, Inc., 1999.

[5] Danielson B Amaral and Igor Schneider. Fins into limbs: Recent insights from sarcopterygian fish. *genesis*, 56(1):e23052, 2018.

[6] ARGO. *Frontier 750 scout 8x8*, Accessed June 3, 2020. https://argoatv.com/intl/archived-vehicles/frontier-750-scout-8x8.

[7] Miriam A Ashley-Ross, S Tonia Hsieh, Alice C Gibb, and Richard W Blob. Vertebrate land invasions–past, present, and future: an introduction to the symposium, 2013.

[8] Yasemin Ozkan Aydin, Baxi Chong, Chaohui Gong, Jennifer M Rieser, Jeffery W Rankin, Krijn Michel, Alfredo G Nicieza, John Hutchinson, Howie Choset, and Daniel I Goldman. Geometric mechanics applied to tetrapod locomotion on granular media. In *Conference on Biomimetic and Biohybrid Systems*, pages 595–603. Springer, 2017.

[9] Hosain Bagheri, Vishwarath Taduru, Sachin Panchal, Shawn White, and Hamidreza Marvi. Animal and robotic locomotion on wet granular media. In *Conference on Biomimetic and Biohybrid Systems*, pages 13–24. Springer, 2017.

[10] Neil J Balmforth, Ian A Frigaard, and Guillaume Ovarlez. Yielding to stress: recent developments in viscoplastic fluid mechanics. *Annual Review of Fluid Mechanics*, 46:121–146, 2014.

[11] Graham Barnes. *Soil mechanics: principles and practice.* Macmillan International Higher Education, 2016.

[12] Philip J Bergmann, Kyle J Pettinelli, Marian E Crockett, and Erika G Schaper. It's just sand between the toes: how particle size and shape variation affect running performance and kinematics in a generalist lizard. *Journal of Experimental Biology*, 220(20):3706–3716, 2017.

[13] R Biseswar. Burrowing, locomotion and other movements of the echiuran ochetostoma caudex. *Acta Zoologica*, 72(2):91–99, 1991.

[14] Patrick JS Boaden and Raymond Seed. *An introduction to coastal ecology.* Springer, 1985.

[15] Catherine A Boisvert. The pelvic fin and girdle of panderichthys and the origin of tetrapod locomotion. *Nature*, 438(7071):1145–1147, 2005.

[16] L Bruzzone and Giuseppe Quaglia. Locomotion systems for ground mobile robots in unstructured environments. *Mechanical sciences*, 3(2):49–62, 2012.

[17] John WM Bush and David L Hu. Walking on water: biolocomotion at the interface. *Annu. Rev. Fluid Mech.*, 38:339–369, 2006.

[18] James Che and Kelly M Dorgan. It's tough to be small: dependence of burrowing kinematics on body size. *Journal of Experimental Biology*, 213(8):1241–1250, 2010.

[19] James Che and Kelly M Dorgan. Mechanics and kinematics of backward burrowing by the polychaete cirriformia moorei. *Journal of Experimental Biology*, 213(24):4272–4277, 2010.

[20] Jennifer A Clack. The fin to limb transition: new data, interpretations, and hypotheses from paleontology and developmental biology. *Annual Review of Earth and Planetary Sciences*, 37:163–179, 2009.

[21] Dennis L Claussen, Jon Snashall, and Chris Barden. Effects of slope, substrate, and temperature on forces associated with locomotion of the ornate box turtle, terrapene ornata. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 138(3):269–276, 2004.

[22] Katherine A Corn, Stacy C Farina, Adam P Summers, and Alice C Gibb. Effects of organism and substrate size on burial mechanics of english sole, parophrys vetulus. *Journal of Experimental Biology*, 221(18):jeb176131, 2018.

[23] P Coussot. Yield stress fluid flows: A review of experimental data. *Journal of Non-Newtonian Fluid Mechanics*, 211:31–49, 2014.

[24] RL Crane and RA Merz. Mechanical properties of sediment determine burrowing success and influence distribution of two lugworm species. *Journal of Experimental Biology*, 220(18):3248–3259, 2017.

[25] Nicole Danos and George V Lauder. Challenging zebrafish escape responses by increasing water viscosity. *Journal of Experimental Biology*, 215(11):1854–1862, 2012.

[26] J Davenport. Locomotion in hatchling leatherback turtles dermochelys coriacea. *Journal of Zoology*, 212(1):85–101, 1987.

[27] J Davenport and AKM Abdul Matin. Terrestrial locomotion in the climbing perch, anabas testudineus (bloch)(anabantidea, pisces). *Journal of Fish Biology*, 37(1):175–184, 1990.

[28] Stephen M Deban and Nadja Schilling. Activity of trunk muscles during aquatic and terrestrial locomotion in ambystoma maculatum. *Journal of Experimental Biology*, 212(18):2949–2959, 2009.

[29] Blake V DICKSON and Stephanie E PIERCE. How (and why) fins turn into limbs: insights from anglerfish. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, 109(1-2):87–103, 2019.

[30] Kelly M Dorgan. The biomechanics of burrowing and boring. *Journal of Experimental Biology*, 218(2):176–183, 2015.

[31] Kelly M Dorgan. Kinematics of burrowing by peristalsis in granular sands. *Journal of Experimental Biology*, 221(10):jeb167759, 2018.

[32] Kelly M Dorgan, Sanjay R Arwade, and Peter A Jumars. Burrowing in marine muds by crack propagation: kinematics and forces. *Journal of Experimental Biology*, 210(23):4198–4212, 2007.

[33] Kelly M Dorgan, Catherine D'Amelio, and Sara M Lindsay. Strategies of burrowing in soft muddy sediments by diverse polychaetes. *Invertebrate Biology*, 135(4):287–301, 2016.

[34] Kelly M Dorgan, Peter A Jumars, Bruce Johnson, BP Boudreau, and Eric Landis. Burrow extension by crack propagation. *Nature*, 433(7025):475–475, 2005.

[35] Kelly M Dorgan, Chris J Law, and Greg W Rouse. Meandering worms: mechanics of undulatory burrowing in muds. *Proceedings of the Royal Society B: Biological Sciences*, 280(1757):20122948, 2013.

[36] Kelly M Dorgan, Stephane Lefebvre, Jonathon H Stillman, and MAR Koehl. Energetics of burrowing by the cirratulid polychaete cirriformia moorei. *Journal of Experimental Biology*, 214(13):2202–2214, 2011.

[37] KM Dorgan. Environmental constraints on the mechanics of crawling and burrowing using hydrostatic skeletons. *Experimental mechanics*, 50(9):1373–1381, 2010.

[38] James L Edwards. Two perspectives on the evolution of the tetrapod limb. *American Zoologist*, 29(1):235–254, 1989.

[39] HUGH Y ELDER. Direct peristaltic progression and the functional significance of the dermal connective tissues during burrowing in the polychaete polyphysia crassa (oersted). *Journal of Experimental Biology*, 58(3):637–655, 1973.

[40] WK Fales, David William Amick, and Barton G Schreiner. The riverine utility craft (ruc). Technical report, SAE Technical Paper, 1971.

[41] Peter L Falkingham and Angela M Horner. Trackways produced by lungfish during terrestrial locomotion. *Scientific reports*, 6(1):1–10, 2016.

[42] Z Faulkes and D Paul. Digging in sand crabs (decapoda, anomura, hippoidea): interleg coordination. *Journal of Experimental Biology*, 200(4):793–805, 1997.

[43] Brooke E Flammang, Apinun Suvarnaraksha, Julie Markiewicz, and Daphne Soares. Tetrapod-like

pelvic girdle in a walking cavefish. *Scientific reports*, 6:23711, 2016.

[44] Kathleen L Foster, Misha Dhuper, and Emily M Standen. Fin and body neuromuscular coordination changes during walking and swimming in polypterus senegalus. *Journal of Experimental Biology*, 221(17):jeb168716, 2018.

[45] GEH Foxon. Xl.—observations on the locomotion of some arthropods and annelids. *Journal of Natural History*, 18(106):403–419, 1936.

[46] Alex A Francoeur and Kelly M Dorgan. Burrowing behavior in mud and sand of morphologically divergent polychaete species (annelida: Orbiniidae). *The Biological Bulletin*, 226(2):131–145, 2014.

[47] Benjamin M Friedrich, Ingmar H Riedel-Kruse, Jonathon Howard, and Frank Jülicher. High-precision tracking of sperm swimming fine structure provides strong test of resistive force theory. *Journal of Experimental Biology*, 213(8):1226–1234, 2010.

[48] Nicholas J Gidmark, James A Strother, Jaquan M Horton, Adam P Summers, and Elizabeth L Brainerd. Locomotory transition from water to sand and its effects on undulatory kinematics in sand lances (ammodytidae). *Journal of Experimental Biology*, 214(4):657–664, 2011.

[49] Francisco A Godínez, Lyndon Koens, Thomas D Montenegro-Johnson, Roberto Zenit, and Eric Lauga. Complex fluids affect low-reynolds number locomotion in a kinematic-dependent manner. *Experiments in Fluids*, 56(5):97, 2015.

[50] Ashok K Goel, Christian Tuchez, William Hancock, and Keith Frazer. Is biologically inspired design domain independent? In *Design Computing and Cognition'16*, pages 157–171. Springer, 2017.

[51] Daniel I Goldman. Colloquium: Biophysical principles of undulatory self-propulsion in granular media. *Reviews of Modern Physics*, 86(3):943, 2014.

[52] Daniel I Goldman and David L Hu. Wiggling through the world: The mechanics of slithering locomotion depend on the surroundings. *American Scientist*, 98(4):314–323, 2010.

[53] Susann Grill and Kelly M Dorgan. Burrowing by small polychaetes–mechanics, behavior and muscle structure of capitella sp. *Journal of Experimental Biology*, 218(10):1527–1537, 2015.

[54] Sten Grillner. Control of locomotion in bipeds, tetrapods, and fish. *Comprehensive physiology*, pages 1179–1236, 2011.

[55] Freyr Hardarson. *Locomotion for difficult terrain*. Citeseer, 1998.

[56] VERNON A HARRIS. On the locomotion of the mud-skipper periophthalmus koelreuteri (pallas):(gobiidae). In *Proceedings of the Zoological Society of London*, volume 134, pages 107–135. Wiley Online Library, 1960.

[57] Clyde F Herreid. *Locomotion and energetics in arthropods*. Springer Science & Business Media, 2012.

[58] Anthony Herrel, Hon Fai Choi, Elizabeth Dumont, Natalie De Schepper, Bieke Vanhooydonck, Peter Aerts, and Dominique Adriaens. Burrowing and subsurface locomotion in anguilliform fish: behavioral specializations and mechanical constraints. *Journal of Experimental Biology*, 214(8):1379–1385, 2011.

[59] Angela M Horner and Bruce C Jayne. The effects of viscosity on the axial motor pattern and kinematics of the african lungfish (protopterus annectens) during lateral undulatory swimming. *Journal of Experimental Biology*, 211(10):1612–1622, 2008.

[60] Angela M Horner and Bruce C Jayne. Lungfish axial muscle function and the vertebrate water to land transition. *PloS one*, 9(5), 2014.

[61] Shi-Tong Tonia Hsieh. A locomotor innovation enables water-land transition in a marine fish. *PloS one*, 5(6), 2010.

[62] RD Hunter, VA Moss, and HY Elder. Image analysis of the burrowing mechanisms of polyphysia crassa (annelida: Polychaeta) and priapulus cudatus (priapulida). *Journal of Zoology*, 199(3):305–323, 1983.

[63] Mayuko Iwamoto, Daishin Ueyama, and Ryo Kobayashi. The advantage of mucus for adhesive locomotion in gastropods. *Journal of theoretical biology*, 353:133–141, 2014.

[64] Alf G Johnels. The mode of terrestrial locomotion in clarias. *Oikos*, 8(2):122–129, 1957.

[65] Sandy M Kawano and Richard W Blob. Propulsive forces of mudskipper fins and salamander limbs during terrestrial locomotion: implications for the invasion of land. *Integrative and comparative biology*, 53(2):283–294, 2013.

[66] Islam SM Khalil, Ahmet Fatih Tabak, Abdelrahman Hosney, Abdalla Mohamed, Anke Klingner, Maged Ghoneima, and Metin Sitti. Sperm-shaped magnetic microrobots: Fabrication using electrospinning, modeling, and characterization. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1939–1944. IEEE, 2016.

[67] Heather M King, Neil H Shubin, Michael I Coates, and Melina E Hale. Behavioral evidence for the evolution of walking and bounding before terrestriality in sarcopterygian fishes. *Proceedings of the National Academy of Sciences*, 108(52):21146–21151, 2011.

[68] Matthew A Klein, Alexander S Boxerbaum, Roger D Quinn, Richard Harkins, and Ravi Vaidyanathan. Seadog: A rugged mobile robot for surf-zone applications. In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, pages 1335–1340. IEEE, 2012.

[69] Tiana Kohlsdorf, Theodore Garland Jr, and Carlos A Navas. Limb and tail lengths in relation to substrate usage in tropidurus lizards. *Journal of morphology*, 248(2):151–164, 2001.

[70] Shigeru Kuroda, Itsuki Kunita, Yoshimi Tanaka, Akio Ishiguro, Ryo Kobayashi, and Toshiyuki Nakagaki. Common mechanics of mode switching in locomotion of limbless and legged animals. *Journal of the Royal Society interface*, 11(95):20140205, 2014.

[71] Giovanni La Spina, Michael Sfakiotakis, Dimitris P Tsakiris, Arianna Menciassi, and Paolo Dario. Polychaete-like undulatory robotic locomotion in unstructured substrates. *IEEE Transactions on Robotics*, 23(6):1200–1212, 2007.

[72] Chris J Law, Kelly M Dorgan, and Greg W Rouse. Relating divergence in polychaete musculature to different burrowing behaviors: a study using opheliidae (annelida). *Journal of morphology*, 275(5):548–571, 2014.

[73] Chen Li, Paul B Umbanhowar, Haldun Komsuoglu, and Daniel I Goldman. The effect of limb kinematics on the speed of a legged robot on granular media. *Experimental mechanics*, 50(9):1383–1393, 2010.

[74] Chen Li, Paul B Umbanhowar, Haldun Komsuoglu, Daniel E Koditschek, and Daniel I Goldman. Sensitive dependence of the motion of a legged robot on granular media. *Proceedings of the National Academy of Sciences*, 106(9):3029–3034, 2009.

[75] Chen Li, Tingnan Zhang, and Daniel I Goldman. A resistive force model for legged locomotion on granular media. In *Adaptive Mobile Robotics*, pages 433–440. World Scientific, 2012.

[76] Chen Li, Tingnan Zhang, and Daniel I Goldman. A terradynamics of legged locomotion on granular media. *science*, 339(6126):1408–1412, 2013.

[77] Xu Liang, Min Xu, Lichao Xu, Peng Liu, Xiaoshuang Ren, Ziwen Kong, Jie Yang, and Shiwu Zhang. The amphihex: A novel amphibious robot with transformable leg-flipper composite propulsion mechanism. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3667–3672. IEEE, 2012.

[78] Stephen Carl Licht, Martin Wibawa, Franz S Hover, and Michael S Triantafyllou. Towards amphibious robots: Asymmetric flapping foil motion underwater produces large thrust efficiently. Technical report, Massachusetts Institute of Technology. Sea Grant College Program, 2009.

[79] Jeanette L Lim and M Edwin DeMont. Kinematics, hydrodynamics and force production of pleopods suggest jet-assisted walking in the american lobster (homarus americanus). *Journal of Experimental Biology*, 212(17):2731–2745, 2009.

[80] Luis O Lucifora and Aldo I Vassallo. Walking in skates (chondrichthyes, rajidae): anatomy, behaviour and analogies to tetrapod locomotion. *Biological Journal of the Linnean Society*, 77(1):35–41, 2002.

[81] Jesus H Lugo, Vishal Ramadoss, Matteo Zoppi, and Rezia Molfino. Conceptual design of tetrad-screw propelled omnidirectional all-terrain mobile robot. In *2017 2nd International Conference on Control and Robotics Engineering (ICCRE)*, pages 13–17. IEEE, 2017.

[82] Ryan D Maladen, Yang Ding, Chen Li, and Daniel I Goldman. Undulatory swimming in sand: subsurface locomotion of the sandfish lizard. *science*, 325(5938):314–318, 2009.

[83] Ryan D Maladen, Yang Ding, Paul B Umbanhowar, Adam Kamor, and Daniel I Goldman. Mechanical models of sandfish locomotion reveal principles of high performance subsurface sand-swimming. *Journal of The Royal Society Interface*, 8(62):1332–1345, 2011.

[84] Hamidreza Marvi, Chaohui Gong, Nick Gravish, Henry Astley, Matthew Travers, Ross L Hatton, Joseph R Mendelson, Howie Choset, David L Hu, and Daniel I Goldman. Sidewinding with minimal slip: Snake and robot ascent of sandy slopes. *Science*, 346(6206):224–229, 2014.

[85] Nicole Mazouchova. *Principles of fin and flipper locomotion on granular media*. PhD thesis, Georgia Institute of Technology, 2012.

[86] Nicole Mazouchova, Paul B Umbanhowar, and Daniel I Goldman. Flipper-driven terrestrial locomotion of a sea turtle-inspired robot. *Bioinspiration & biomimetics*, 8(2):026007, 2013.

[87] Benjamin McInroe, Henry C Astley, Chaohui Gong, Sandy M Kawano, Perrin E Schiebel, Jennifer M Rieser, Howie Choset, Richard W Blob, and Daniel I Goldman. Tail use improves performance on soft substrates in models of early vertebrate land locomotors. *Science*, 353(6295):154–158, 2016.

[88] Rachel Ann Merz and Deirdre Renee Edwards. Jointed setae–their role in locomotion and gait transitions in polychaete worms. *Journal of experimental marine biology and ecology*, 228(2):273–290, 1998.

[89] Elizabeth AK Murphy and Kelly M Dorgan. Burrow extension with a proboscis: mechanics of burrowing by the glycerid hemipodus simplex. *Journal of Experimental Biology*, 214(6):1017–1027, 2011.

[90] Kenji Nagaoka, Masatsugu Otsuki, Takashi Kubota, and Satoshi Tanaka. Terramechanics-based propulsive characteristics of mobile robot driven by archimedean screw mechanism on soft soil. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4946–4951. IEEE, 2010.

[91] J Nieder. Amphibious behaviour and feeding ecology of the four-eyed blenny (dialommus fuscus, labrisomidae) in the intertidal zone of the island of santa cruz (galapagos, ecuador). *Journal of Fish Biology*, 58(3):755–767, 2001.

[92] MAKAR OFFROAD. *The Burlak*, Accessed June 3, 2020. https://makaroffroad.com/models/burlak.

[93] FERGUS O'GORMAN. Observations on terrestrial locomotion in antarctic seals. In *Proceedings of the Zoological Society of London*, volume 141, pages 837–850. Wiley Online Library, 1963.

[94] CM Pace and Alice C Gibb. Mudskipper pectoral fin kinematics in aquatic and terrestrial environments. *Journal of Experimental Biology*, 212(14):2279–2286, 2009.

[95] CM Pace and Alice C Gibb. Sustained periodic terrestrial locomotion in air-breathing fishes. *Journal of fish biology*, 84(3):639–660, 2014.

[96] Lipika Parida, Udita Uday Ghosh, and Venkat Padmanabhan. The effects of groove height and substrate stiffness on c. elegans locomotion. *Journal of biomechanics*, 55:34–40, 2017.

[97] PHIBION. *The Mudmaster*, Accessed June 3, 2020. https://www.phibion.com/the-mudmaster.

[98] CJC Phillips and ID Morris. The locomotion of dairy cows on concrete floors that are dry, wet, or covered with a slurry of excreta. *Journal of dairy science*, 83(8):1767–1772, 2000.

[99] Stephanie E Pierce, Jennifer A Clack, and John R Hutchinson. Three-dimensional limb joint mobility in the early tetrapod ichthyostega. *Nature*, 486(7404):523–526, 2012.

[100] Raymond H Plaut. Mathematical model of inchworm locomotion. *International Journal of Non-Linear Mechanics*, 76:56–63, 2015.

[101] CAROLINE M POND. The role of the 'walking legs' in aquatic and terrestrial locomotion of the crayfish austropotamobius pallipes (lereboullet). *Journal of Experimental Biology*, 62(2):447–454, 1975.

[102] Alexander J Pronko, Benjamin M Perlman, and Miriam A Ashley-Ross. Launches, squiggles and pounces, oh my! the water–land transition in mangrove rivulus (kryptolebias marmoratus). *Journal of Experimental Biology*, 216(21):3988–3995, 2013.

[103] KJ Quillin. Ontogenetic scaling of burrowing forces in the earthworm lumbricus terrestris. *Journal of Experimental Biology*, 203(18):2757–2770, 2000.

[104] Yegor Rabets, Matilda Backholm, Kari Dalnoki-Veress, and William S Ryu. Direct measurements of drag forces in c. elegans crawling locomotion. *Biophysical Journal*, 107(8):1980–1987, 2014.

[105] Marc Raibert, Kevin Blankespoor, Gabriel Nelson, and Rob Playter. Bigdog, the rough-terrain quadruped robot. *IFAC Proceedings Volumes*, 41(2):10822–10825, 2008.

[106] KV Reshma, K Amudha, C Janarthanan, NR Ramesh, K Gopakumar, GA Ramadass, and MA Atmanand. Experimental study on sinkage and breakout forces for soft soil. In *2015 IEEE Underwater Technology (UT)*, pages 1–5. IEEE, 2015.

[107] AL Rice and CJ Chapman. Observations on the burrows and burrowing behaviour of two mud-dwelling decapod crustaceans, nephrops norvegicus and goneplax rhomboides. *Marine Biology*, 10(4):330–342, 1971.

[108] RIPSAW. *The Ripsaw tank*, Accessed June 2, 2020. http://www.ripsawtank.com/.

[109] Norihiko Saga and Taro Nakamura. Development of a peristaltic crawling robot using magnetic fluid on the basis of the locomotion mechanism of the earthworm. *Smart materials and structures*, 13(3):566, 2004.

[110] Martin DJ Sayer. Adaptations of amphibious fish for surviving life out of water. *Fish and Fisheries*, 6(3):186–211, 2005.

[111] Michael Sfakiotakis, Avgousta Chatzidaki, Theodoros Evdaimon, Asimina Kazakidi, and Dimitris P Tsakiris. Effects of compliance in pedundulatory locomotion over granular substrates. In *2016 24th Mediterranean Conference on Control and Automation (MED)*, pages 532–538. IEEE, 2016.

[112] Sarah S Sharpe, Robyn Kuckuk, and Daniel I Goldman. Controlled preparation of wet granular media reveals limits to lizard burial ability. *Physical biology*, 12(4):046009, 2015.

[113] SHERP. *The Sherp ATV*, Accessed June 3, 2020. https://sherpatv.com/.

[114] Siddharth Shrivastava, Andras Karsai, Yasemin Ozkan Aydin, Ross Pettinger, William Bluethmann, Robert O Ambrose, and Daniel I Goldman. Material remodeling and unconventional gaits facilitate locomotion of a robophysical rover over granular terrain. *Science Robotics*, 5(42), 2020.

[115] Emily M Standen, Trina Y Du, Philippe Laroche, and Hans CE Larsson. Locomotor flexibility of polypterus senegalus across various aquatic and terrestrial substrates. *Zoology*, 119(5):447–454, 2016.

[116] BAE SYSTEMS. *The bvs10-beowulf*, Accessed June 2, 2020. https://www.baesystems.com/en/product/bvs10-beowulf.

[117] Theresa-Anne M Tatom-Naecker and Mark W Westneat. Burrowing fishes: Kinematics, morphology and phylogeny of sand-diving wrasses (labridae). *Journal of fish biology*, 93(5):860–873, 2018.

[118] Evgenij Telezhenko and Christer Bergsten. Influence of floor type on the locomotion of dairy cows. *Applied Animal Behaviour Science*, 93(3-4):183–197, 2005.

[119] Baptiste Darbois Texier, Alejandro Ibarra, and Francisco Melo. Helical locomotion in a granular medium. *Physical review letters*, 119(6):068003, 2017.

[120] TINGER. *The Tinger track*, Accessed June 2, 2020. http://tingeratv.com/model/tr/.

[121] Barry Trimmer and Jonathan Issberner. Kinematics of soft-bodied, legged locomotion in manduca sexta larvae. *The Biological Bulletin*, 212(2):130–142, 2007.

[122] Barry A. Trimmer, Ann E Takesian, and Brian M Sweet. Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. In *International Symposium on Technology and the Mine Problem*, 2006.

[123] ER Trueman. The mechanism of burrowing of the mole crab, emerita. *Journal of Experimental Biology*, 53(3):701–710, 1970.

[124] ER Trueman. Locomotion in molluscs. In *The mollusca*, pages 155–198. Elsevier, 1983.

[125] ER Trueman, AR Brand, and P Davis. The dynamics of burrowing of some common littoral bivalves. *Journal of Experimental Biology*, 44(3):469–492, 1966.

[126] Dimitris P Tsakiris, A Menciassi, M Sfakiotakis, G La Spina, and P Dario. Undulatory locomotion of polychaete annelids: mechanics, neural control and robotic prototypes. In *Annual Computational Neuroscience Meeting, Baltimore, USA*, 2004.

[127] AJ Turko and PA Wright. Evolution, ecology and physiology of amphibious killifishes (cyprinodontiformes). *Journal of Fish Biology*, 87(4):815–835, 2015.

[128] DE Van Dijk. Locomotion and attitudes of the mudskipper, periophthalmus, a semi-terrestrial fish. *South African Journal of Science*, 56(7):158–162, 1960.

[129] JEAN VANNIER, PHILIPPE BOISSY, and PATRICK R RACHEBOEUF. Locomotion in nebalia bipes: a possible model for palaeozoic phyllocarid crustaceans. *Lethaia*, 30(2):89–104, 1997.

[130] Paul-Armand Verhaegen, Joris D'hondt, Dennis Vandevenne, Simon Dewulf, and Joost R Duflou. Identifying candidates for design-by-analogy. *Computers in Industry*, 62(4):446–459, 2011.

[131] Julian FV Vincent, Olga A Bogatyreva, Nikolaj R Bogatyrev, Adrian Bowyer, and Anja-Karina Pahl. Biomimetics: its practice and theory. *Journal of the Royal Society Interface*, 3(9):471–482, 2006.

[132] Marvalee H Wake. Tetrapod limbless locomotion. *e LS*, 2001.

[133] Lei Wang, Min Xu, Bo Liu, Tianyu Jiang, Shiwu Zhang, and Jie Yang. Experimental study on morphology and kinematics of mudskipper in amphibious environments. In *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 1095–1100. IEEE, 2013.

[134] Richard J Wassersug. Locomotion in amphibian larvae (or "why aren't tadpoles built like fishes?"). *American zoologist*, 29(1):65–84, 1989.

[135] Adhityo Wicaksono, Saifullah Hidayat, Bambang Retnoaji, Adolfo Rivero-Müller, and Parvez Alam.

A mechanical piston action may assist pelvic–pectoral fin antagonism in tree-climbing fish. *Journal of The Marine Biological Association of The United Kingdom*, 98(8):2121–2131, 2018.

[136] Brian J Williams, Sandeep V Anand, Jagannathan Rajagopalan, and M Taher A Saif. A self-propelled biohybrid swimmer at low reynolds number. *Nature communications*, 5(1):1–8, 2014.

[137] AG Winter, RLH Deits, DS Dorsch, AH Slocum, AE Hosoi, et al. Razor clam to roboclam: burrowing drag reduction mechanisms and their robotic adaptation. *Bioinspiration & biomimetics*, 9(3):036009, 2014.

[138] Amos G Winter, Robin LH Deits, and Anette E Hosoi. Localized fluidization burrowing mechanics of ensis directus. *Journal of experimental biology*, 215(12):2072–2080, 2012.

[139] DW Yalden. The anatomy of mole locomotion. *Journal of Zoology*, 149(1):55–64, 1966.

[140] Tingnan Zhang and Daniel I Goldman. The effectiveness of resistive force theory in granular locomotion. *Physics of Fluids*, 26(10):101308, 2014.

[141] Yan Zhang, Jiafeng Cao, Qi Wang, Pengfei Wang, Yueying Zhu, and Junxia Zhang. Motion characteristics of the appendages of mole crickets during burrowing. *Journal of Bionic Engineering*, 16(2):319–327, 2019.

[142] Yan Zhang, He Huang, Xiangyang Liu, and Luquan Ren. Kinematics of terrestrial locomotion in mole cricket gryllotalpa orientalis. *Journal of Bionic Engineering*, 8(2):151–157, 2011.

[143] Zhi-Qiang Zhang. Phylum arthropoda. in: Zhang, z.-q.(ed.) animal biodiversity: An outline of higher-level classification and survey of taxonomic richness (addenda 2013). *Zootaxa*, 3703(1):17–26, 2013.

[144] Bin Zhong, Youcheng Zhou, Xiaoxiang Li, Min Xu, and Shiwu Zhang. Locomotion performance of the amphibious robot on various terrains and underwater with flexible flipper legs. *Journal of Bionic Engineering*, 13(4):525–536, 2016.

[145] ZIL. *The ZIL-2906*, Accessed June 3, 2020. https://www.tfloffroad.com/2018/08/the-dangerous-past-the-zil-2906-the-screw-drive-all-terrain-russian-soviet-awesomeness/.

Appendix A Systematic literature review

For identifying the relevant papers, we conducted a keyword search relating to the terms locomotion, animal and low-yield environment. While conducting the search we found new keywords from the identified papers and added them to our keyword list. The final list of keywords is the following: {amphibious, animals, benthic, boring, burrowing, clay, flowable, fossorial, intertidal, legged, locomotion, low resistance, mangrove, motion, mud, multiphase, sand, semi-terrestrial, slurry, soft, substrate, unstructured, viscoplastic, walking, weak ground, wet granular media}.

The search was conducted through online databases (Google Scholar, IEEExplore, ACM Digital Library, Science Direct, WebofScience, Wiley Online Library, Scopus, CiteseerX, Springerlink, PNAS, PlosOne) in which we looked for as many combinations of our keywords as possible (e.g. "animal locomotion in multiphase environment", "walking fish on mud", "legged locomotion on low resistance ground"). Additional papers were identified from the references of the found papers. To insure inclusiveness, all papers mentioning any of our keywords were selected in the first phase of search. Out of this first step, 216 papers mentioning our keywords were listed.

Then, the second step consisted of reading the abstracts of the papers. Only the papers dealing with the locomotion aspect from the mechanical perspective were kept; for example the papers dealing with genomic evolution, neural control, muscle control, fishes swimming while close to a surface, or analysis of the anatomy from an evolution perspective were ousted. At the end of this second phase, 116 papers were kept in our selection.

The third phase was to identify the main topic of the papers and to categorise them based on that topic. The outcome of the categorisation can be found in table 1, and the related references in table 2.

In the fourth step, we disregarded some papers out of scope for our literature review (e.g. addressing the effect of viscosity on swimming or the burrowing patterns of crustaceans). This left us with 104 papers. Table 3 shows the distribution of the papers according to their category. This distribution shows the clear emphasize on worms, mudskippers, arthropods and sarcopterygian fishes, which together account for more than half of the papers.

The fifth and final step was to read each of these papers and keep the most representative of each category. Those papers are closer discussed in this overview.

Topic	Papers	Number of papers
Burrowing /loco of an annelid	25,26,27,28,29,31,39,43,55,56,68,69,81,97,110,116,	16
Model of granular media + parameters for locomotior	10,32,35,57,58,59,60,66,86,91,107,115,	12
Mudskipper	112,21,48,53,67,70,73,72,85,101,103,	11
Arthropods	39,62,79,99,108,111,119,120,11	8
Locomotion/swimming in sand/granular media	42,64,65,86,89,121,122,	7
Nematode	1,5,15,74,82,110,	6
Lungfish	2,33,47,52,113,114,	6
Burrowing/loco using hydrostatic skeleton	9,8,22,24,23,84,	6
Digging in crustaceans	34,,83,94,99,	5
Tetrapod locomotion	37,76,100,117,19,53	5
Evolution Water to land	4,6,12,30,	4
Turtle on ground	13,17,32,66,	4
Sarcopterygian fishes	3,52,113,	3
polypterus senegalus on land	38,87,88,	3
Viscosity and swimming speed	41,16,114,	3
caterpillars	78,92,93,	3
Burrowing and locomotion of molluscs	95,96,105,	3
Climbing perch on land	18,85,	2
Description of burrowing/locomotion vs substrate pr	23,86,	2
Transition water to sand/burrowing	40,46,	2
Robots locomotion for difficutl terrain	45,109,	2
Catfish on land	51,72,	2
Influence of slurry on the locomotion of cows	75,90,	2
Sperm/flagela	104,118,	2
Walking on water	7,	1
Burial anf effects of size on bury	14,	1
Development of limbs in walking benthic fishes	20,	1
Salamander model granular media	36,	1
Basilik lizard on wet granular media	35,	1
Coastal ecology, sediments	44,	1
Gastropods	49,	1
Turtle robot in water	61,	1
Skate exhibits a tetrapod-like walking pattern	63,	1
Seals moving on land	70,	1
Mangrove rivulus	80,	1
Killifish	98,	1
Mole locomotion/burrowing	106,	1

Table 1. Categorisation of the papers according to their topic. The green lines are the topics which were selected on the next selection step, while the gray and white are undifferentiated. The column "number of papers" doesn't add up to 122 because some of the papers were not included in the categorisation due to the fact that they were a redundancy of another paper published in a different format, and some papers belong to several categories. See references in table 2.

Index	Reference	Ind.	Ref.	Ind.	Ref.
1	[1]	2	[3]	3	[5]
4	[7]	5	[13]	6	[15]
7	[17]	8	[19]	9	[18]
10	N/A	11	N/A	12	[20]
13	[21]	14	[22]	15	[24]
16	[25]	17	[26]	18	[27]
19	[28]	20	[29]	21	[128]
22	[37]	23	[30]	24	[31]
25	[32]	26	[33]	27	[34]
28	[35]	29	[36]	30	[38]
31	[39]	32	[85]	33	[41]
34	[42]	35	[9]	36	[8]
37	[43]	38	[44]	39	[45]
40	[48]	41	[49]	42	[51]
43	[53]	44	[14]	45	[55]
46	[58]	47	[60]	48	[61]
49	[63]	50	N/A	51	[64]
52	[67]	53	[65]	54	[69]
55	[71]	56	[72]	57	[73]
58	[74]	59	[76]	60	[75]
61	[78]	62	[79]	63	[80]
64	[82]	65	[83]	66	[86]
67	[87]	68	[88]	69	[89]
70	[91]	71	[93]	72	[95]
73	[94]	74	[96]	75	[98]
76	[99]	77	N/A	78	[100]
79	[101]	80	[102]	81	[103]
82	[104]	83	[107]	84	[109]
85	[110]	86	[112]	87	[115]
88	N/A	89	[117]	90	[118]
91	[119]	92	[122]	93	[121]
94	[123]	95	[125]	96	[124]
97	[126]	98	[127]	99	[129]
100	[132]	101	[133]	102	[134]
103	[135]	104	[136]	105	[138]
106	[139]	107	[140]	108	[143]
109	[144]	110	[62]	111	[57]
112	[56]	113	N/A	114	[59]
115	[106]	116	[46]	117	[54]
118	[47]	119	[142]	120	[141]
121	[12]	122	[52]		

Table 2. References of all the documents kept after the first analyse. This includes all the papers considered as in relation with our topic: all the papers excluded in the first step were excluded after reading of the abstract, all the papers put aside on the next step are because of the refinement of our problem on a strictly mechanical and biologically focused problem, as well as the deletion of the several publications of a same research (rare cases). The N/A labels indicate documents deleted in the steps described.

Topic	Papers	Number of papers
Worms	25,26,27,28,29,31,39,43,55,56,68,69,81,97,110,116,9,8,22,24,23,84,1,5,15,74,82,11	28
Mudskipper	112,21,48,53,67,70,73,72,85,101,103,	11
Arthropods	39,62,79,99,108,111,119,120,11,	9
Sarcopterygian fishes	4,6,12,30,3,52,113,20,	8
Locomotion/swimming in sand/granular media	42,64,65,86,89,121,122,	7
Lungfish	2,33,47,52,113,114,	6
Tetrapod locomotion	37,76,100,117,19,53,	6
Turtle on ground	13,17,32,66,	4
polypterus senegalus on land	38,87,88,	3
caterpillars	78,92,93,	3
Burrowing and locomotion of molluscs	95,96,105,	3
Climbing perch on land	18,85,	2
Transition water to sand/burrowing	40,46,	2
Catfish on land	51,72,	2
Influence of slurry on the locomotion of cows	75,90,	2
Sperm/flagela	104,118,	2
Basilik lizard on wet granular media	35,	1
Gastropods	49,	1
Seals moving on land	70,	1
Mangrove rivulus	80,	1
Killifish	98,	1
Mole locomotion/burrowing	106,	1
TOTAL		104

Table 3. Selection of the categories made depending on their sensibility. Some categories were merged together.