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Actuated Bivalve Robot
Study of the Burrowing Locomotion in Sediment

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Abstract— **This paper presents the design and control of an actuated bivalve robot, which has been developed to study the burrowing locomotion of bivalves in sediment. The setup consists of a tank filled with sand and water, plastic models of bivalve shells capable of expelling water and an external actuation mechanism simulating the rocking burrowing motion typically used by these animals. The realistic shell shapes have been realized using three-dimensional plotting techniques allowing testing influences of different shell shapes and surface structures (sculptures) on the burrowing efficiency.**

Based on the experimental setup, the burrowing process has been reproduced. The results show that this setup can be used to identify correlations in the burrowing process. Further experimental work will investigate the influence of factors such as shell shape and sculpture or the motion sequence on the burrowing performance.

Keywords: biorobotics; biomimetics; burrowing locomotion; bivalves

I. INTRODUCTION

Bivalves have been part of the animal world for a long period of time and are well adapted to their particular mode of life. Our focus lies on their locomotion behavior, which in many cases consists of burrowing into the sediment for protection against predators and other environmental factors. This behavior provides an excellent instance of a well defined and well studied process suited to test novel methodological approaches. In our project, we pursue an "understanding by building" approach, as we built a robotic experimental setup to investigate bivalve burrowing without using living animals. The total control of the morphology and actuation of the artificial bivalves allows a systematic examination of the burrowing process by varying single parameters. We intend to use the constructed platform to shed light on correlations of morphology, motion and sediment and thus better understand the link between morphology and functionality.

There are several reasons why clams are used to study correlations between morphology and behavior. First, suitable mathematical models of bivalve shell morphology already exist. Second, the mechanical behavior of bivalves, which mainly consists of burrowing into the sediment, is simple when compared to other organisms. Third, in contrast to other animals, bivalves do not use a complicated system of multiple movable body parts or the secretion of mucus to burrow. Such complex dynamics would be much harder to simulate. And fourth, a large range of shells with different shapes and sculptures is easily available.

It is technically difficult to get close to living bivalves. Therefore we lay our focus on comparing robots among each other while systematically varying parameters instead of trying to authentically mimic specific species or individuals. The built platform is able to burrow artificial bivalves into the sediment using a simple, externally actuated shell model. The correlation between burrowing efficiency, shape, sculpture and size can be established.

A further goal is to understand the burrowing process so that energy saving sequences can be defined to dig and anchor objects in sediment for sea applications. A study analyzing real bivalve behavior in sediment shows that the surrounding sediment is fluidized through the opening and closing of shells [1]. It appears essential to mimic the natural behavior and liquidize the soil during digging in order to reduce the soil resistance.

In this paper, the design and control of the bivalve robot is described. An experimental apparatus based on an aquarium tank containing water and sediment is presented. The experimental setup allows simulating the burrowing locomotion in sediment. Experimental results illustrate the characteristics of burrowing locomotion for digging into substrates. The discussion describes the biological relevance of the platform and in the future work section, we explain which additional functionalities will be integrated into the setup and which further experiments will be performed to identify correlations between morphology and burrowing performance.

II. RELATED WORK

A. Bivalve Shape

The soft body of bivalves is enveloped by two valves which are dorsally connected and pushed open by an elastic ligament. The valves of burrowing clams are closed by usually two adductor muscles. The part inside the shell not

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occupied by the animal body is called the mantle cavity. A part of the soft body called foot protrudes ventrally from the shell and plays a major role in the burrowing process. Depending on the species, the shell sculptures have characteristic structures such as concentric ridges. It has been discovered that the shell features have a function and tend to enhance burrowing efficiency [2] [3].

Bivalve shells, as the shells of the related gastropods (snails) have a convoluted shape. One of the first attempts to mathematically model this shape was done by Raup [4] in 1965, where he also introduced the term "theoretical morphology". Since then, many different approaches have been suggested, but most of them are based on a simple growth process that produces a sequence of aperture curves of increasing size that travel along a three-dimensional helicospiral (see also [5], [6], [7], [8], [9], [10]). Only a few parameters are needed to generate realistic virtual shell shapes.

B. Bivalve Burrowing

In order to burrow themselves into the sediment, bivalves use a two-anchor system. The shell and a part of the soft body called foot alternate in anchoring the bivalve in the sediment, while the other is pushed or pulled forward. Anchoring is done by increasing the size: the shells are opened, the foot swells under blood pressure. The dynamics of this process were first described in greater detail by Trueman [1]. He identified the motion sequence described in fig. 1 which is called the "burrowing sequence". He observed the behavior of littoral bivalves making films through the glass of an aquarium tank.

In natural bivalves, valve adduction happens in about 0.1 s, immediately followed by the anterior and posterior pedal retraction. After the relaxing of the adductor muscles to reopen the valves and a rest period, the next burrowing cycle begins. With increasing depth, the rest period tends to become longer and the depth increase per burrowing cycle smaller. Small and rapid burrowers reach their living position in just a few seconds (e.g. *Donax denticulatus* in 3 to 11 s). Shallow burrowers live only 1 to 3 cm below the sediment surface, whereas deep burrowers move to a depth of 20 cm and more (up to 100 cm). In particular cases (e.g. *Divaricella quadrisulcata*), this is more than ten times the body size [11].

It was recognized early on that the morphology of the shell and foot have a large impact on the burrowing performance. A notable physical experiment was performed in 1975 by Stanley [12]. He produced a cast of a specimen of *Mercenaria mercenaria* that has a blunt anterior area and tested it in real sediment. He simulated the rocking burrowing motion by manually and alternately pushing two rods attached to the shell. By comparing the burrowing performance to a second model where he had altered the shape to display a sharper front edge, he could explain the advantage of the blunt anterior region of this particular species.

Bivalve morphologies suitable for efficient burrowing and correlations between morphology, burrowing motion and sediment have already been detected. Stanley found that ridges at a right angle to the burrowing direction are advantageous and used with rocking motions covering a small angle, while v-shaped ridges are also possible, leading to larger rotation angles [13]. Savazzi [14] summarizes that the sculpture amplitude increases with sediment grain size, that the profile of the sculpture should be asymmetric and the gentle slope should be facing the burrowing direction. Using our experimental setup, we intend to verify these and similar findings and generate new ones.

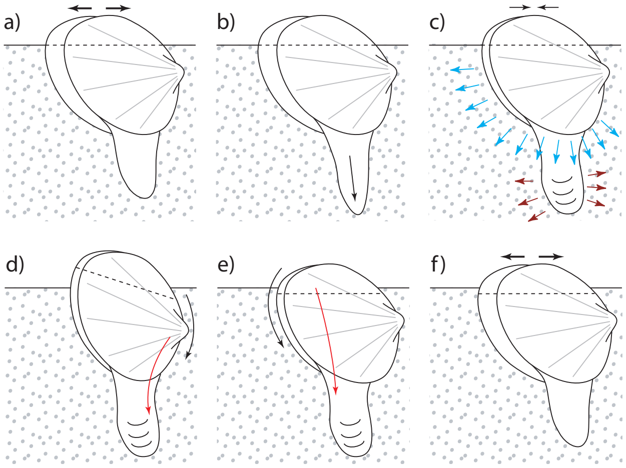

Fig. 1. The *burrowing sequence* for bivalves as described by Trueman [1]. (a) The clam is in erect position, partially burrowed in the sediment. The valves are open to anchor the shell, i.e. to prevent back-slippage. (b) The foot probes deeper into the sediment. (c) The adductor muscles contract, partially closing the shell. The water expelled from the cavity liquefies the surrounding sediment to reduce the resistance to penetration. From the soft body inside the shell, blood is pressed into the foot, which is inflated and serves as a new anchor. (d) The anterior retractor muscle (red arrow) pulls the front side of the bivalve towards the foot, leading to a rotation of the shell (black arrow). (e) In the same way, the posterior retractor muscle rotates the shell back into the erect position. (f) The two rotations around different rotation axes led to a net downward translation, as illustrated by the dashed line. The valves open again to allow for another burrowing cycle starting at (a).

C. Burrowing Robots

Although there have been a few burrowing robots, most of them are conceived of as applications in a bionics context. An interesting approach is the RoboClam from the Hatsopoulous Microfluidics Laboratory at MIT (Massachusetts Institute of Technology) which mimics the behavior of the razor clam to perform anchoring operations [15] [16]. The project focuses on the *Ensis* clam genus, an elongate species by which the shell digs into sediment without rocking motion. The robot is actuated using pneumatic pistons which apply forces to push the razor clam into the sediment. The efficiency of clam digging has been demonstrated in comparison to standard anchoring techniques.

Another example of a burrowing robot is a soft-bodied climbing system named Softbot [17]. This robot is not inspired from bivalves but from caterpillars, that are capable to crawl and burrow into confined spaces.

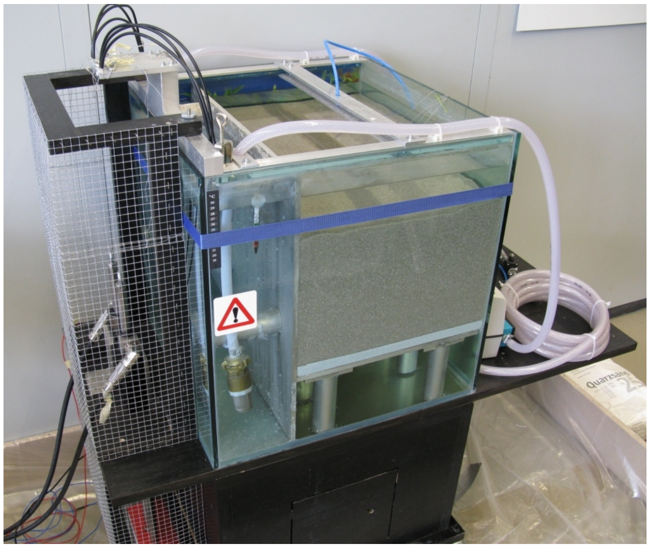

Fig. 2. The experimental setup consisting of an actuation mechanism (left), a tank filled with sediment and water (middle) and a hydraulic system for water expulsion (right).

III. METHODS AND MATERIALS

Figure 2 shows the complete experimental apparatus, which has been realized to investigate the burrowing behavior of bivalves in sediment. It consists of three main parts: (1) an aquarium tank, (2) an actuation mechanism and (3) a hydraulic system. The aquarium with the dimensions of 60×60×60 cm (216 ℓ) is filled with sediment and water. Since the sediment is deposited onto a bottom plate, it can be exchanged to investigate the influence of sediment characteristics on the burrowing process. The tank has been filled with normal tap water and some anti-algae solution. The first experiments were done with a simple unwashed sand with grain sizes between 0 and 4 mm. Later and future experiments were or will be conducted with a well-rounded quartz sand with grain sizes between 0.7 and 1.2 mm, which falls in the category of coarse to very coarse sand. After being placed at the interface between water and sediment, the bivalve robot can perform its burrowing motion in sediment. A number of parameters determining the morphology and behavior of the robot bivalves can be varied, including the overall shell shape, the amount and shape of radial and commarginal sculpture and the operation timing during the burrowing cycle.

A. Robot Bivalve Shells

It is well recognized in malacological research that the shell morphology has a major impact on the burrowing performance. To study the relationships between physical morphology and burrowing efficiency, a dedicated software tool has been developed in order to generate different complex forms of virtual shells. The program uses a mathematical model similar to the one described in [5]. To print the generated model on a 3D printer, it has to be transformed from an open surface into a closed solid. This has been achieved by closing both sides of the tubular mesh with disk-like patches. The patch closing the aperture is either flat or manually designed by a computer aided design (CAD) program. The former allows gluing two parts together to produce a one-piece shell, while the latter may be used to equip the shell with an attachment site that fits to the inner structure of a more complicated robot. The final result is a closed triangle mesh that is stored in STL format and can be directly sent to the 3D printer.

Fig. 3. Left: Real bivalve shell (*Cardium pseudolima*). Right: A similar shell, artificially generated and realized with a 3D plotter.

A *dimension*® *bst 768* 3D printer [18] and its *CatalystEx* software has been used to print the shells. The shells are printed in solid mode to avoid the plastic from absorbing too much water. The resolution of the printer is about 0.5 mm. Available bivalve specimen can be scanned by computed tomography to get virtual geometrical models of their shells. This approach allows the fabrication of one-piece shells as well as thin-walled half-shells. They have an outside geometry close to real bivalves but can also include robotic components in the inner cavity. Figure 3 depicts both a specimen of *Cardium pseudolima* and a shell model realized by 3D plotting.

B. Burrowing Motion

According to the burrowing sequence described in [1], the downward digging and the rocking along the longitudinal axis have been implemented in the bivalve robot. Linear electrical motors integrated into the setup provide a flexible actuation solution to perform digging operations.

As shown in Figure 4, bivalve shells are pulled downward using two strings which are actuated externally by LinMot motors. These two linear actuators (called left and right motors) are synchronized to obtain the rocking down-motion of the bivalve. Motor parameters such as rocking step resolution and time can be varied. Force and position are monitored using the control unit of the motors. Pulling forces up to 200 N and a maximum stroke of 66 cm can be obtained with this configuration.

The system control has been implemented in the motor control box using LinMot-Talk [19]. Based on PID position controllers, a response time of 10 ms and a positioning accuracy of 30 µm have been achieved, which is sufficient for reproducing the burrowing motion.

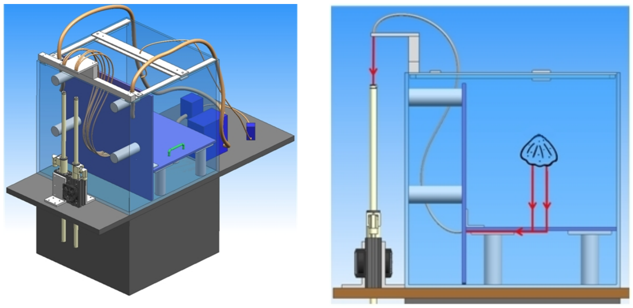

Fig. 4. Two schematic drawings of the bivalve model, the tank and the actuation mechanism. The red arrows show the track of the strings that are attached to the shell and to two linear motors that pull the bivalve into the sediment. The strings are deviated to avoid cutting the glass bottom of the tank. To reduce the friction on the string, it only runs through the sand right below the shell. After passing through a hole in the horizontal plate, it is led through water and a cable casing.

C. Burrowing Efficiency

To perform a comparison between several burrowing strategies for a given species, it is particularly relevant to define a parameter called burrowing efficiency which indicates the mechanical energy E_{mech} required to reach a defined burrowing depth in sediment. The necessary energy shall be kept as low as possible to obtain an optimized burrowing locomotion.

$$E_{mech} = F_d v t_d \tag{1}$$

The burrowing efficiency, given in Equation 1, depends on three parameters: the pulling force F_d, the average speed v and the digging time t_d. As introduced by Trueman [2], the bivalve mass shall be considered to compare the burrowing efficiency among bivalves of varying sizes. Therefore, the burrowing efficiency parameter $E_{mech,s}$ includes a shell body mass parameter m_s and is represented by Equation 2.

$$E_{mech,s} = \frac{F_d}{m_s} v t_d \tag{2}$$

D. Water Expulsion

Vertical digging of an object into sediment under water requires extremely large forces so that the necessary energy to reach a digging depth in soil increases drastically. It has been observed early on that real bivalves use water expulsion combined with rocking motion to fluidize sediment and therefore facilitate the digging process.

Water expulsion has been simulated using a hydraulic pump which is connected to the bivalve. Perforated tubing has been inserted into the shells to allow water expulsion along the bivalve edge. The water pressure p is regulated between 0.1 and 1.0 bar by a pressure regulation valve. The membrane pump generates a volume flow Q between 0.5 and 3.0 ℓ/min. A two-position two-way valve is integrated into the liquid path to block the liquid flow when closed. The valve command signal is generated by the controller of the electrical motors. The hydraulic parameters have been set so that the amount of water expelled per cycle corresponds to the volume expelled from the mantle cavity during the closing of the shells. For energy comparison, the hydraulic energy E_{hydr} required for water expulsion must be added to the mechanical energy E_{mech} supplied for the rocking motion. The total energy E_t required for burial is given by Equation 3.

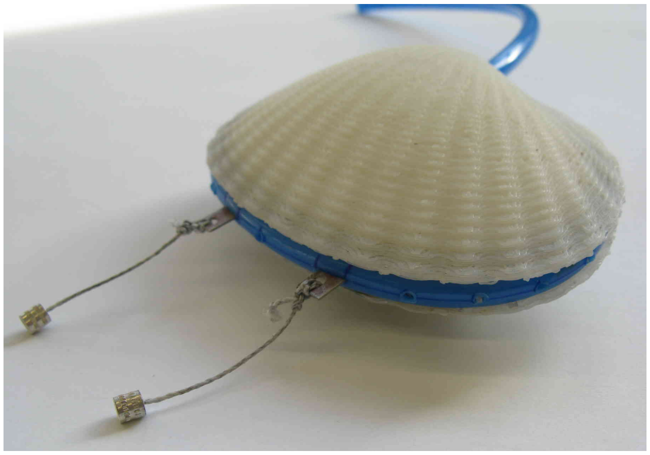

Fig. 5. Burrowing robot design including water expulsion mechanism. A plastic shell includes a peripheral rubber tube with holes to emit water. The tube is connected to the hydraulic pump placed next to the tank.

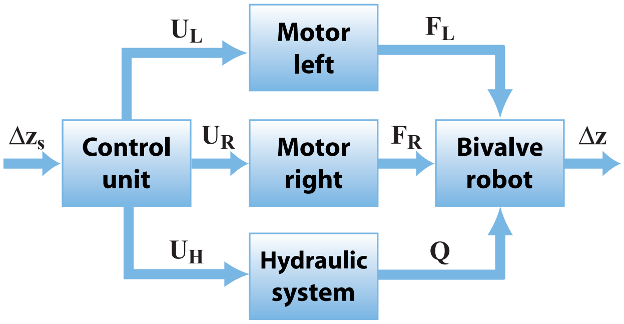

Fig. 6. Control Scheme for the bivalve robot. The control unit generates commands to the linear motors and the hydraulic system to obtain the burrowing motion.

$$E_t = E_{mech} + E_{hydr} \tag{3}$$

where E_{hydr} depends on the volume flow and the hydraulic pressure.

The Figure 6 illustrates the control scheme. The control unit is in charge of the synchronization between rocking motion and water expulsion in order to reach a defined depth Δz_s. The command unit generates control voltages U_R and U_L to the motor amplifiers as well as on/off commands U_H to the hydraulic valve. The motors generate alternate forces F_R and F_L to pull down the bivalve robot. The water flows through the robot when the hydraulic valve is opened.

IV. RESULTS

Several burrowing sequences have been tested experimentally. After the robot has been brought to the sediment surface, the burrowing process has been started. Under the

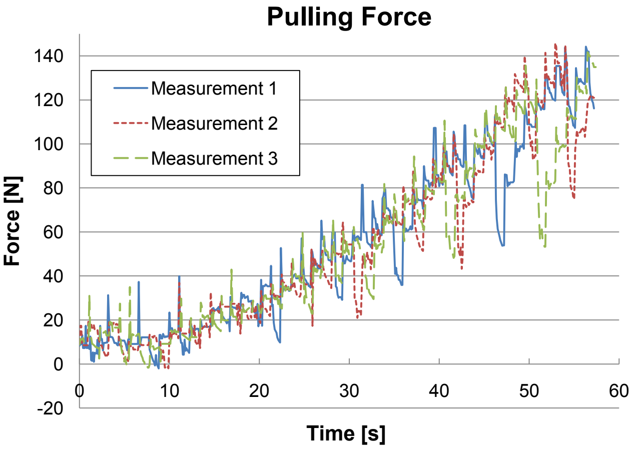

Fig. 7. Measured digging force generated by linear motors to pull the bivalve robot into sediment. The graph shows the results of three successive runs of the same burrowing experiment. For each run, the force applied by the left (posterior) motor is plotted against time. During this burrowing period, the shell was pulled 10 cm into the sediment by regular steps of 2 mm. The force measurements are fairly repeatable even if environmental conditions cannot be completely identical from one experiment to another.

assumption that the strings do not deform, the information about force and position provided by the motor control unit are good indicators about the burrowing efficiency of the bivalve robot.

A. *Burrowing Motion*

Repeated measurements on the pulling forces F_R and F_L generated by the motors have shown that these forces increase almost linearly with the digging depth Δz measured from the sediment surface. Although initial conditions for each experiment cannot be completely identical due to sediment's sinking effects, the force measurements are fairly repeatable, as illustrated on Figure 7. The pulling forces increase slowly in the first 10 mm in sediment because only a small part of the bivalve is covered by sand. Since the forces generated by the right and left motors are similar, only the force of the left motor (simulating the posterior retractor muscle) is represented for a better graph readout.

By performing displacement steps of 2 mm every 1.1 s, alternately with the left and right motors, the bivalve reaches a depth of 100 mm in about 57 s. Force values between 0 and 144 N have been measured during a burrowing sequence. Measured short force peaks can be explained by inhomogeneities and density variations in the substrate. The closed-loop position control system leads to significant force deviations along the path, depending on whether the bivalve is in contact with compacted or loose sediment.

B. *Water Expulsion*

To investigate the impact of sediment fluidization on the burrowing efficiency, several experiments have been performed with and without water expulsion. To prevent a motor overload, these measurements can be done only for a reduced depth in sediment.

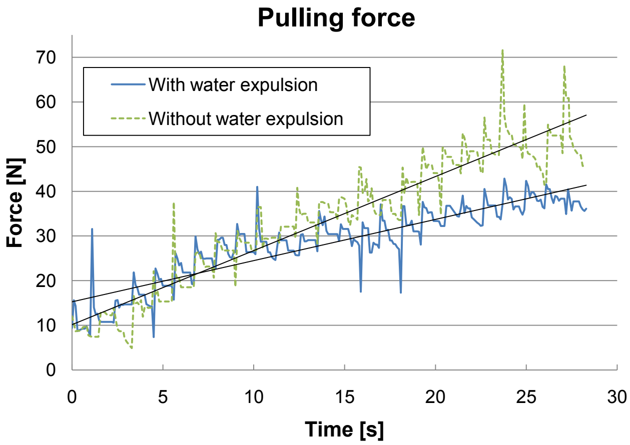

Fig. 8. Comparison of force profiles for a burrowing motion when water is expelled or not from the bivalve shells. The water was ejected through a perforated tube along the commissure of the two valves. For these experiments, the pump was operated at full capacity. During the whole period, the shell was pulled 5 cm into the sediment. At the beginning, there was no noticeable difference, but after about 10 s, water expulsion reduced the necessary force to pull the shell deeper into the sediment. The linear trendlines are plotted for lucidity, the intersection is of no known significance.

Figure 8 illustrates the forces necessary to pull downward the burrowing robot into sediment. In the initial phase, the required forces are fairly similar since the bivalve is located at the boundary between water and sediment. After the transition phase, a significant force reduction is observed if water expulsion is active. When the bivalve robot digs into the sediment to a final depth of 50 mm, the required force has been reduced by a factor of 1.7. Since the bivalve robot is position controlled, water expulsion has no influence on the digging time but improves the burrowing efficiency by a factor of 1.7.

V. DISCUSSION

A. *Proposed Approach*

This paper describes the design and realization of an experimental setup to investigate the burrowing locomotion of bivalves. This apparatus consists of bivalve shells generated using geometric growth models and realized as plastic objects by a 3D printer, a tank providing an underwater sandy environment and an external actuation system. Current results have shown that artificial clams can be burrowed and that the setup allows collecting very useful data about the burrowing process and the influence of different factors such as overall shape, sculpture, burrowing parameters and water expulsion.

B. *Biological Relevance*

During the burrowing process, bivalves press water out of the mantle cavity and into the surrounding sediment. This is done by quick contractions of the adductor muscles to partially close the shell. Since this was discovered, it has been assumed that the resulting loosening of the sediment reduces the resistance to penetration. It could be shown experimentally that the rocking motion combined to sediment fluidization enables significant energy savings for digging operations.

A major criterion for the usefulness of the proposed setup is its ability to authentically mimic biological bivalve morphology and burrowing behavior. The closeness to nature is limited by several technical restrictions.

(a) The current geometric model allows only radial and com-marginal sculptures and mixtures of the two (leading to a coffered pattern). It is not possible to generate skew, asymmetric or locally varying sculptures. (b) The size of the printed shells lies in the upper range of natural shell sizes (about 10 cm). This is partly due to the limited printer resolution. Consequently, we use sand with grain sizes slightly above average (0 to 4 mm and 0.7 to 1.2 mm). But it cannot be expected that all the relevant physical processes scale to the used magnitude. (c) The density distribution of an artificial bivalve made of ABS (acrylonitrile butadiene styrene) shells and inner metal parts is different from a natural bivalve consisting of calcite/aragonite and organic material. (d) The rotation axes during the burrowing sequence depend on the attachment location of the muscles/strings. While the muscles of living bivalves work on contact points dorsally inside the shell, the strings in our setup are tied to a metal part ventrally protruding from the shell. (e) All soft body parts including the foot are currently missing.

VI. FUTURE WORK

Ongoing experiments consist in testing different shell shapes in order to understand their role in the burrowing locomotion. A more sophisticated geometric model that allows skew sculpture will allow testing a larger variety of different shells. The influence of sediment has also to be further investigated. In particular, the influence of grain size on the burrowing performance is to be analyzed in correlation with the shell morphology.

The final goal is to develop an autonomously burrowing robot including an anchoring foot to mimic the bivalve behavior. In a first step, the water expulsion mechanism using rubber tubes will be replaced by and compared to an artificial bivalve with shells that can be opened and closed. In a seconds step, a mechanically autonomous burrowing robot will be realized by adding an artificial foot made from soft material.

VII. ACKNOWLEDGMENTS

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