REALITIES OF BIOLOGICALLY INSPIRED DESIGN WITH A SUBTERRANEAN DIGGING ROBOT EXAMPLE

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Abstract

The design of novel robotic systems is a complex and challenging practice. The evolutionary process in nature can be of aid to engineers who study the background biological literature relating to creatures with an ability that is required to be replicated. The potential benefits of biomimetic design have been shown by researchers for different areas of robotic locomotion. This work discusses the challenges spanning these two diverse research fields for the example application of a digging robot; a field of robotic locomotion yet to benefit from biological inspiration.

Keywords: Biomimetic design, digging robot, *talpa* mole functional morphology.

Introduction

The state of the art of robotics research generally results in novel mechanical systems of a high degree of complexity. During this design and development process the performance of a particular function will likely be subject to conflicting criteria leading to necessary and possibly limiting trade-offs. Through the study of relevant examples in nature, robotics designers can exploit the evolution process and take biological inspiration from the functional morphology of specialised creatures well-known for excelling in the activity of interest. Research into biomimetic design has demonstrated the potential performance improvements with examples of walking [1, 2], flying [3] and swimming [2, 4] robots.

Walking robots offer the advantage over wheeled or tracked alternatives by being able to step over obstacles, a useful property in areas where the terrain is unknown. Raibert has produced founding work on walking robots such as experiments into running gates of a quadruped robot [5]. The quadruped is, however, not stable at low walking speeds and the statically stable gait of 6-legged (hexapod) robots has led biomimetic researchers to study insects. Ritzmann *et al* [6] built a biologically inspired robot based on their studies of the locomotion of a cockroach. They applied their "biology-as-default" approach where design decisions were based on biology even when the advantage was not immediately apparent. Laksanacharoen *et al* [7] simulated a robotic cricket which had the ability to jump over obstacles using its hind legs. Altendorfer *et al* [8] produced a robot with a bouncing gate based on studies of a running cockroach. One important benefit was that of energy efficient locomotion, which becomes increasingly important with autonomous un-tethered robots. This further supports biological inspiration, as efficient locomotion can be seen in many examples in nature [9].

Flying robots exhibiting a high level agility is an extremely attractive concept and would have a very wide range of applications. In nature the hummingbird exhibits significant placement control whilst flying and hovering. Raney and Slominski [10] used functional morphology as inspiration for a micro air vehicle (MAV). The wing layout, flexibility and natural frequency were replicated and it was shown to generate wing flapping when forced at resonance. The wing provided up force on both strokes through flexing, which an earlier paper by Dickinson *et al* [11] based on insect hovering was able to do by mechanical rotation of the wings about their own axis.

Biologically inspired swimming robots would potentially present stealth and manoeuvrability benefits way beyond those of propeller driven craft. Moreover, it can be seen that in nature fish exploit vortices to maximise propulsion efficiency [9]. Triantafyllou and Triantafyllou [12] showed that by bringing the Strouhal number (vortex production frequency multiplied by wake width divided by flow speed) of their robotic tuna to be within that in nature they were able to obtain significantly higher efficiency than previously achieved. Barrett *et al* [13] later experimentally showed a reduction in drag on a swimming robotic fish compared to when it was rigid. Mason and Burdick [14] created a simplified propulsion model and three-link experimental fish and used both to produce closely agreeing simulation and experimental results respectively. Serpentine creatures have also been used as biological inspiration for swimming mechanisms. McIsaac and Ostrowski [15] built an experimental robotic underwater eel which was able to generate four different swimming gates. Hirose and Fukushima [16] presented current and previous work within their group including *HELIX-I* a snake-like amphibious robot that in water replicated the spiral propulsion seen in Spirochete micro-organisms.

This paper discusses the necessary steps to extract inspiration from nature for the example of digging; an area of robotics yet to be influenced by biology. In the context of this paper, digging involves subterranean tunnelling or burrowing activity, which places restrictions on the size and energy efficiency of operation of the robot particularly if it is un-tethered. This area of research has been extremely neglected. Fukunaga *et al* [17] proposed an earthworm like robot that used peristaltic motion by buckling and hence bracing part of the robot while the rest pushed through the earth. Richter *et al* [18] implemented a probe that propelled itself into the earth using a series of outward and backward hammering actions to compress and push off from the soil respectively. The small number of previous works relied on a device of small cross section that was able to push its way through the earth and negated the need for digging action. Existing subterranean digging/boring machines are extremely large and heavy devices used in civil applications and remove earth by rotating and shearing earth and gradually progressing further. They are highly energy inefficient, do not employ intelligent control and are not able to alter their course if an impassable object is encountered. Self propelled robots that employ manipulators and intelligent control to dextrously remove earth from their pathway have not been covered in the literature.

The following section discusses the background biological literature studied and how ideas were extracted from the functional morphology. The subsequent section discusses the digging techniques and trajectories employed by the mole. After this the issues involved in implementing these ideas into a biomimetic robot are presented with a conceptual design. The final section details the challenges and necessary steps for general biomimetic design with further concluding remarks and future research aims.

Digging functional morphology

The biomimetic design process (designing robots with the operational principles of animals) begins with a study of the general text books that provide quick access to basic principles and indications for further research. In the context of this paper, the biomimetic process of interest is digging, an activity for which physical shape and size are crucial. Functional morphology can be defined as the study of the form of body parts based upon their operative purpose, the study of which in relation to particular animals can provide useful information. It is, however, important to note that investigating the functional morphology does not necessarily aid in the biomimetic design process. For example, studying the functional morphology of a brain does not provide much insight into how its function.

General text books reveal that there are four main digging mechanisms employed by subterranean animals: Scratch, chisel tooth, head lift and humeral rotation digging [19]. Scratch diggers draw their feet through the earth down and backwards. Chisel tooth diggers use their teeth (and possibly also their claws) to dislodge earth from the tunnel face and then use their limbs to push it behind them. Some animals combine chisel tooth and head lift digging to remove earth. Humeral rotation digging (the animal forelimbs are permanently rotated outwards) presents a methodical mechanism used by animals specialised in digging, which has the potential to inspire a robotic digging system. It has also been well studied in the biological literature with reference to the mole (*talpa europea*).

With the animal of greatest relevance identified, more specialised references provide detail into the separate forelimb bones [20], the forelimb anatomy during digging [21] (Figure 1), the humeral axis of rotation [22] and useful descriptions of the digging process [21, 23].

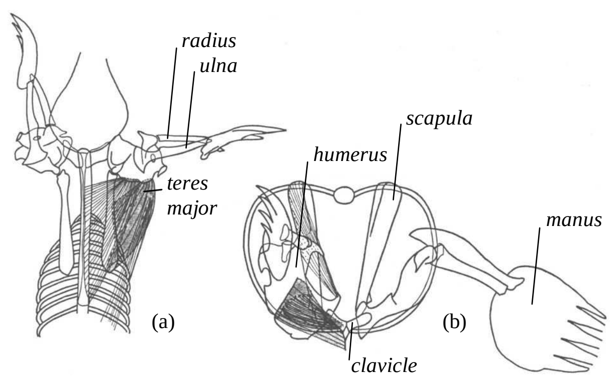

Figure 1 The action of the forelimb skeleton of *talpa* mole. (a) From above, (b) from the front [21]

It is interesting to note that the date of the biological publications provide little indication of their potential relevance in this context. Some of the most insightful works date from the 1950's and 1960's. This is in stark contrast to the field of robotics which is almost reinvented every 10 years.

The style of communicating information in biological papers is significantly different from engineering disciplines such as robotics with biological papers preferring richly detailed anatomical sketches opposed to concise, simplified kinematic diagrams. Therefore, it is necessary to bridge the gap between these approaches by bringing together and interpreting the information from multiple references and constructing a simplified diagram. Figure 2 allows a better understanding of how the mole is able to generate large digging forces. The dashed lines in Figure 2a show the axis of rotation of the humeral bones, which allow the forearms to move through their limits of motion.

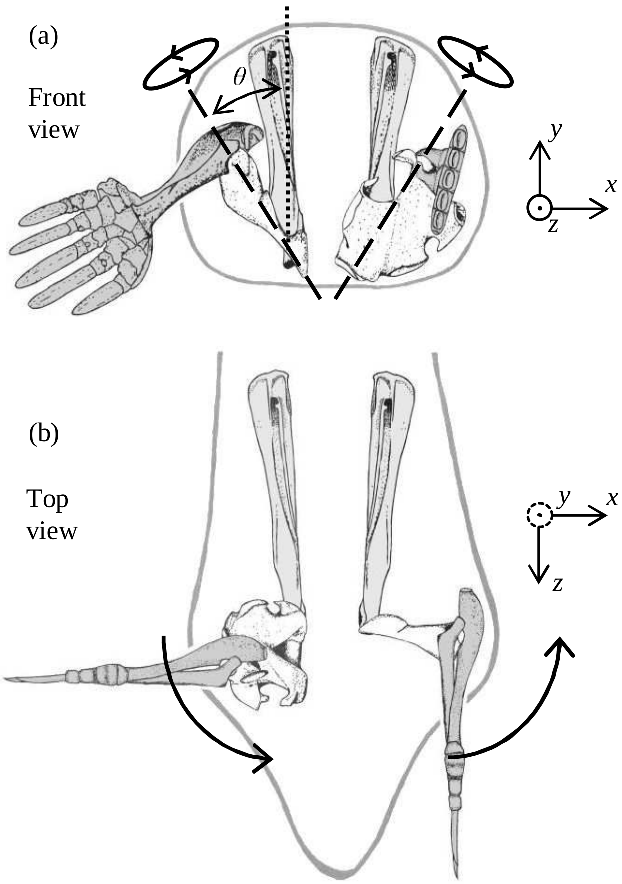

Figure 2 Interpreted diagram of the function morphology of the *talpa* mole forelimb. (a) Front view, (b) top view

The broad hands of the mole are positioned in the vertical plane and move laterally, shearing soil from the tunnel face and pushing it backwards. The large hand height to body height relation allow for efficient extraction of soil. Anatomically the mole is most unusual in that digging is affected through rotation of the humerus about its own long axis. Elbow joint rotation only serves to alter the digging height of the forward tunnel [21]. The digging efficiency is due to the evolved balance between body size and forearm output force. As shown in Figure 1 the mole has evolved a greatly increased humeral width allowing large moments to be placed by the powerful muscle insertions. Of these the dominant *teres major* is anchored at the base of the scapula, a long and slender bone that runs down the back of the mole [23]. The clavicles are short, which locates the humeral bones close together and making up the majority of the width of the mole.

This can be further illustrated mathematically from a lever mechanics point of view as shown in Equation 1 [23] and Figure 3.

$$F_o = \frac{F_i L_i}{L_o} \tag{1}$$

Where,

F_0 = Output Force

F_i = Input Force

L_o = Output Lever Length

L_i = Input Lever Length

All three terms on the right hand side of Equation 1 have evolved to benefit the digging efficiency. The input force, F_i, has been optimised with the large number of powerful muscles. The input lever arm, L_i, has been optimised by increasing the humeral width without an associated increase in the body width. The output lever arm, L_o, has been minimised whilst still providing a useful output stroke length.

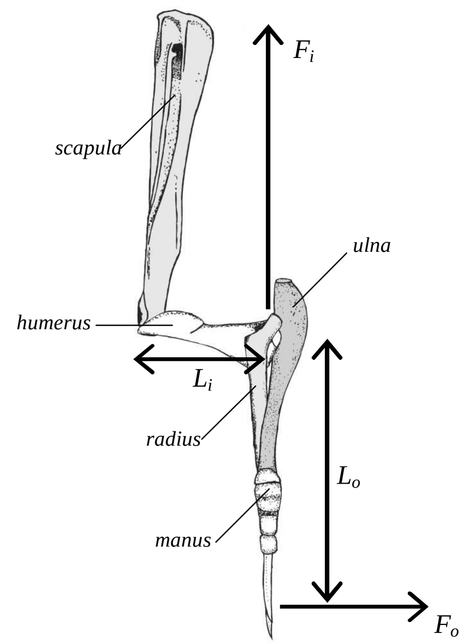

Figure 3 Lever mechanics of the *talpa* mole forelimb

Although the mole has evolved a highly specialised digging ability, the forearm still contain degrees of freedom which are not applicable to this activity, such as movement of the wrist, digits etc. Figure 4 shows a kinematic diagram relating to the left arm in Figure 2a and has reduced the degrees of freedom to rotation of the humerus and rotation at the elbow joint. The diagram shows the useful movement of the mole forearm and gives the engineer information about the mechanical structure of a biomimetic robot. The actuation of the *talpa* mole forearm is provided by a large number of muscles as illustrated in Figure 1 that are attached along both the scapular and humeral bones. A robot may provide actuation in either a rotary (i.e.

electromagnetic motor) or a linear (i.e. pneumatic/hydraulic piston or linear electromagnetic motor) fashion. Of these the former would be placed such that the axis of rotation coincided with that in Figure 4 while the latter would be placed with two anchor points similar to a single muscle but without necessity for a large number of them.

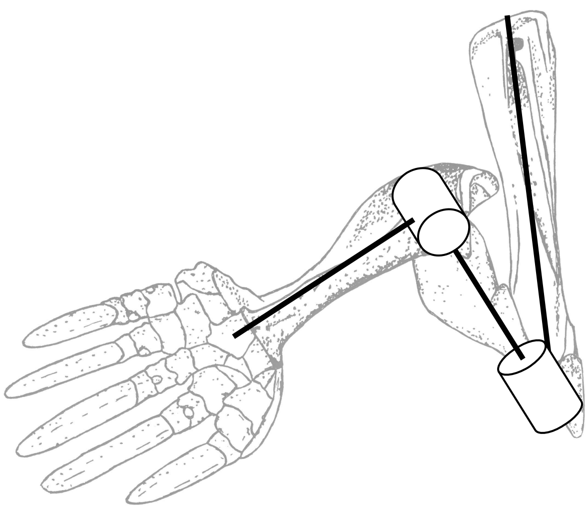

Figure 4 Kinematic representation of the important degrees of freedom of the *talpa* mole forearm

The particular shape of the forearm bones will have evolved to some extent to maximise the effect of the muscles attached along them. Another factor may be the density of the bones which will possibly be non-uniform such that the centre of gravity position of each bone is optimised to further affect the digging performance. Information such as this would be useful to the engineer interested in biomimetic design but unfortunately is unavailable in the biological literature.

Digging technique

The digging action of the mole is affected through rotation of the humerus. The bicep and triceps muscles are weaker than those that rotate the humerus (i.e. *teres major* etc) as they are only required to raise or lower the hand to control the digging height. The alignment of the elbow is, therefore, such that the digging forces are transmitted through the elbow joint rather than the muscles.

The mole only uses one hand at a time to dig, the other being used along with the hind limbs as a position brace. An elliptical motion of the tip of the digging hand is followed which is able to return the hand to the digging start position close to the body to avoid contact with the removed earth or the tunnel walls (Figure 5). This can be accomplished be either rotating the elbow joint or moving the whole position of the mole by changing the position of the bracing arm.

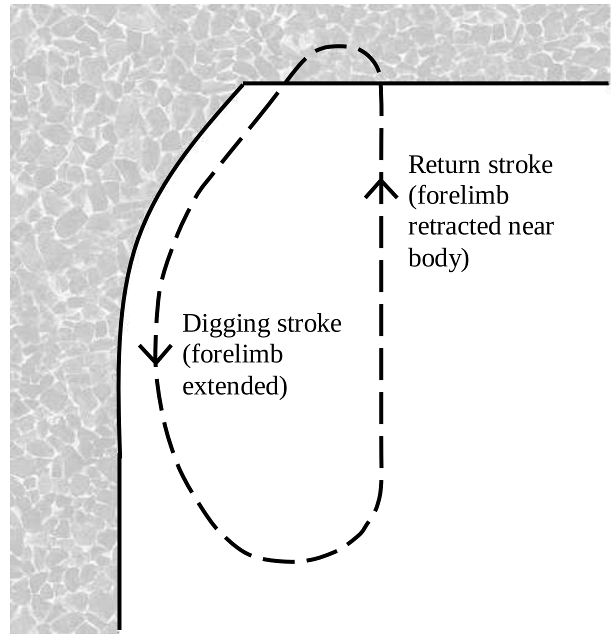

Figure 5 Example tip motion of *talpa* mole forearm during digging

In a general sense the elliptical joint motion during the backward digging stroke means that the hand is only in contact with the tunnel surface for a limited time. Figure 6 compares elliptical digging paths when the humerus is vertical and rotated at an angle, θ, as in nature and indicated in Figure 2. The figure shows successive (slightly overlapping) backward strokes, the direction being indicated with the arrows. With a zero angle rotation the top view shows that the elliptical motion is quite deep and the side view that the digging action does not act in the vertical plane. It can be seen that not only does the natural case have a smaller deviation of sideways digging depth resulting in an increased amount of tunnel wall contact but also contact with a larger vertical height of tunnel wall in a single stroke. These two advantages may help explain the reason for the angle of the humeral rotation axis that would undoubtedly aid the efficiency of the digging of the *talpa* mole. The results shown in Figures 5 and 6 can support trajectory planning in robotic control.

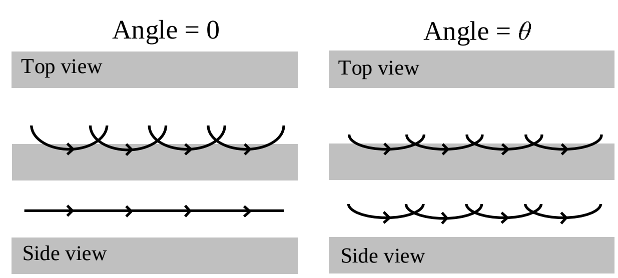

Figure 6 Example digging stroke trajectories for a humeral rotation axis angle of zero and θ

Biomimetic Robot Design

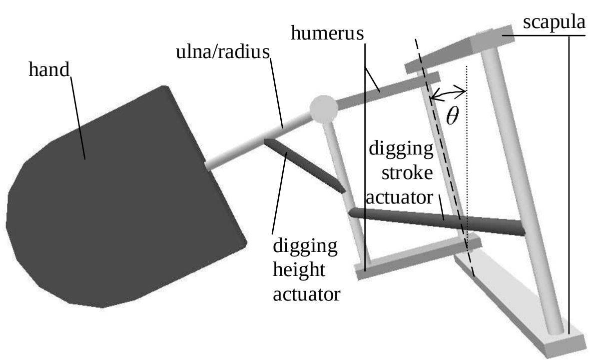

Figure 7 Concept robot *talpa* mole forelimb

This section presents a biomimetic robot concept based on the knowledge gleamed from the biological sources. The design structure is based on that in Figure 4 with important bone dimensions copied from nature. Linear actuators have been employed as they show the most similarity to the operation of biological muscles. The scapula is long and designed to run down the length of the robot chassis such it does not affect the cross section of the mole. The axis of rotation of the humerus in nature is located such that muscle attachments on either side can provide rotation in both directions. Unlike muscles, mechanical actuators are able to provide force in both directions; therefore, it is sensible to locate the axis of rotation at one side of the humerus and the force input at the other. The axis of rotation of the humerus has been angled and results in a default joint position with the lower part of the hand being approximately level with that of the body (i.e. the scapula in Figure 7). Both the humerus and scapula are in two pieces to allow space for pivot joints and actuator location and additionally avoids possible twisting of the joints. The digging stroke actuator has been placed for greatest mechanical advantage and thus mimics the *teres major* muscle. The ulna and radius have been combined into a single joint that rotates as in nature to alter the digging height. The manus/hand is large as in nature and would possibly have small mechanical claws to facilitate removal of debris. The posterior surface shown in Figure 7 would be concave similar to that in nature to scoop the earth more effectively. The two degrees of freedom of the design will allow the robotic mole manipulator tip to follow the trajectories as in nature shown in Figures 5 and 6. It is possible that this may be accomplished in addition to the rotation of the digging arm joints by a controllable movement of the bracing arm joints as in nature.

Conclusions and future work

The paper has investigated and presented the underlying challenges facing the robotics design engineer when trying to gain inspiration from biological research literature for the example application of robotic digging. The general form of the necessary steps are concluded below.

1. Research general text books for initial insight into relevant animals most specialised to perform the activity of interest.
2. Perform in depth research using biological journals on candidate animals.
3. Interpret multiple sources to form simplified anatomical sketches which can be studied in depth.
4. Establish the particular features that allow the biological example to excel in the activity.
5. Analyse the sketches to form kinematic diagrams using biological literature to reduce the complexity to the key components.
6. Incorporate these features into a mechanical robot design while rejecting features that offer no benefit or would reduce the efficiency of operation.

The above steps were followed with the study of the functional morphology of the *talpa* mole; one of the most specialised subterranean diggers. This approach has revealed several key factors that should influence the design of a digging robot:

- The angle θ in Figure 2 is likely to play a significant role in the digging process affecting the digging trajectory.
- The digging hands should be large in relation to the cross section of the body.
- The elbow is aligned so that the large forces generated on the humerus pass across the joint rather than through it.
- Two degrees of freedom for the limbs presents an elegant solution even though three degrees of freedom would be the obvious approach.
- The muscle attachments on the long scapula allow large forces to be placed almost perpendicularly to the humeral bone surface.
- The ratio of bone lengths allows a large force output whilst minimising the mole width.
- The method of digging with one limb while bracing with the others provides a stable method of digging.

The resulting robotic concept in Figure 7 has the potential, after further design modifications, to be incorporated into a digging robot. The design is intended for use with two arms placed on either side of a robot chassis. In order to accomplish this, future goals would need to be achieved which are detailed below. Further analysis of the concept in Figure 7 should be embarked upon to determine optimum dimensions for the components of the robot forelimb. As discussed above the particular size of the mole bones are based on many conditions such as optimising the effectiveness of the spread of muscles etc. Issues such as this are not relevant to the robotic design so directly implementing the bone sizes in nature may not yield an optimum design. They could, however, be used as starting values in an optimisation simulation/algorithm to obtain optimum component size and actuator location to maximise the digging output force whilst minimising the cross-section of the robot and hence the earth that has to be dug through.

Quinn *et al* [24] used McKibben artificial muscles to mimic the leg actuation in a robotic cricket. This could be applied to the robotic digging mechanism, the humerus of which would have to be redesigned to accommodate force inputs at either side of the rotary axis. An investigation into the performance of a linear bi-directional force actuated digging robot and one using artificial muscles may yield interesting results as to the relative efficiency and hence the potential gain of either method.

As biomimetic design is a multidisciplinary process it must take advantage of knowledge from both the areas of biology and engineering. It would, therefore, be advantageous to have experts from both sides in any design team.

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