

## Standard Review

# Review on application of biomimetics in the design of agricultural implements

Benard Chirende<sup>1</sup> and Jianqiao Li<sup>2\*</sup>

Key Laboratory for Terrain-Machine Bionic Engineering (Ministry of Education), Jilin University, Changchun 130022, P.R. China.

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**This paper aims at reviewing the application of biomimetics in design of agricultural implements. Most of the biomimetic works done were aimed at investigating the effect of non-smooth surfaces on soil resistance based on soil burrowing animals. The characteristics of soil-burrowing animals for improved soil scouring and their mechanism for reducing soil adhesion and friction are discussed. From past research works, it can be concluded that non-smooth surfaces can generally reduce soil resistance however the extent of reduction is still a gray area. The main factors affecting soil adhesion like the nature and properties of the soil, the properties of the soil-engaging component surfaces and the experimental conditions which are difficult to replicate, could be the explanation for inconsistencies in the extent of soil resistance reduction. Generally, when applying the concept of non-smooth surfaces in biomimetic implement design, general factors considered in arranging non-smooth structures are distribution of normal stresses, choice of non-smooth type and material, soil motion tracks during operation and choice of non-smooth convex parameters.**

**Key words:** Biomimetics, anti-friction, anti-adhesion, soil resistance, burrowing animals.

## INTRODUCTION

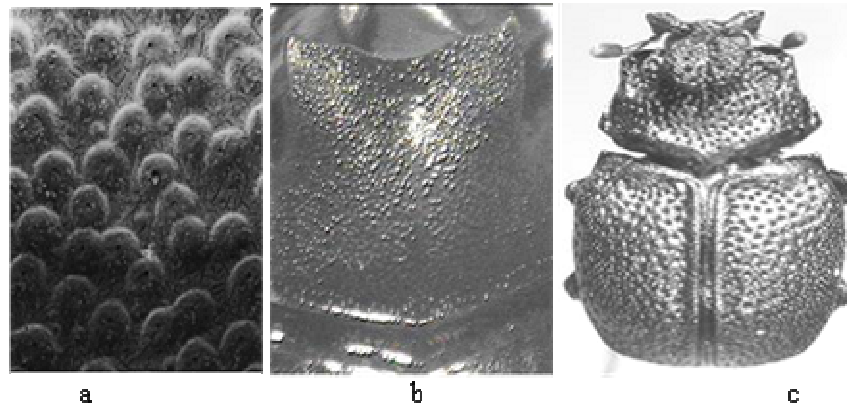
The anti-adhesion and anti-friction functions of a soil burrowing animal body surface against soil are an inevitable outcome of evolution and adaptation over millions of years. The body surface morphology of these animals have non-smooth units such as convex domes, con-cave dips, ridges or wavy structures, which play important roles in their anti-soil adhesion and anti-friction functions. The soil-burrowing animals' soil adhesion techniques have led to some improvement of conventional methods for reducing soil adhesion like in the design of implement surface shapes, selection of surface materials for soil-engaging components and application of electro-osmosis, magnetic fields, vibration and lubrication in implement design. These soil burrowing animals prevent soil from sticking to their bodies because of evolution of their biolo-

gical systems through exchange of matter, energy and information with soil over centuries. They can comfortably move in even clay soil without soil sticking to their bodies. Soil-engaging tools have been designed based on these features of living organisms which are efficient in biomimetic anti-adhesion, anti-friction and anti-abrasion against soil (Tong et al., 2004). Different biomimetic designs were found to have different effects on improving implement performance against soil resistance.

## Characteristics of soil-burrowing animals

Soil-burrowing animals include animals such as dung beetle, ground beetle and mole cricket living in soil and also those which dig burrows in earth without necessarily living in it such as house mouse, yellow mouse and pangolin. The living surroundings of these soil animals are very different from those of animals living on land and in water. It is generally more difficult for animals to move in soil especially when the soil is moist and this has led to

\*Corresponding author. E-mail: [jqli@jlu.edu.cn](mailto:jqli@jlu.edu.cn). Tel.: +86-432-85095760-8407. Fax: +86-431-85095575-8402.



**Figure. 1** The morphological surfaces of dung beetle *Copris ochus Motschulsky*.  
 (a) Stereoscopy image of the clypeus and pronotum of a female dung beetle *Copris ochus Motschulsky*.  
 (b) Stereoscopy image of the pronotum of a male dung beetle *Copris ochus Motschulsky*.  
 (c) Scanning electron microscopy image of the convex domes on pronotum cuticle surface of *Chlamydopsinae* (Moayad, 2004).

their natural adaptation to suit the difficult conditions. The gradual adaptation is evident in their anti-adhesion and anti-friction behaviour. The body surface morphologies, chemical composition, bioelectricity, secretion and flexibility of cuticle of soil-burrowing animals are the main features helping in achieving anti-adhesion and anti-friction functions.

Soil-burrowing animals have geometrically textured structures on their body surfaces. For example, there exist varied textured structures on the clypeus, pronotum, elytra, abdomen and legs of all the *Lamellicornia* beetles (Liu et al., 1997). In addition, the geometrical surface morphologies of earthworm (*Lumbricidae*), centipede (*Chilopoda*), dung beetle (*Scarabaeidae*), ground beetle (*Carabidae*), ant (*Formicidae*), mole cricket (*Gryllotalpidae*) were examined and non-smooth structures were seen on the body surface (Tong et al., 2004). The different morphological features of the body surfaces exist in different species of soil animals as well as in different segments of the same animal.

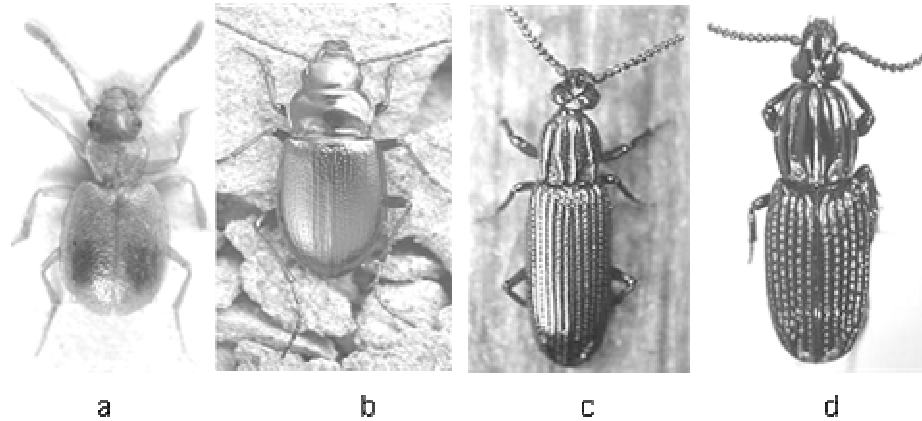
The geometrically textured surfaces include the embossed morphology with small convex domes, dimpled morphology with small concave hollows, wavy morphology, scaly morphology, corrugated morphology with ridges, and seta-covered morphology. For a dung beetle such as *Scarabaeus typhoon Fischer*, *Gymnopleurus mopsus Pallas*, *Sisyphus schaefferi Linnaeus*, the clypeus has a curved shape surface (Moayad, 2004). Figure 1 to 3 illustrate photographs of some beetles and their surface morphologies.

According to Tong et al. (2005), the body surfaces of soil animals have a strong intrinsic hydrophobic nature,

which implies that the force of attraction between the body surface materials and water molecules is very small. From the pronotum surface of dung beetle (*Copris ochus Motschulsky*), it was demonstrated that the apparent contact angles of water on the surface were 91 to 106.5° and the average contact angle was 97.2°, a figure which represents its hydrophobic property (Figure 4). The non-smooth structures on the body surface of these soil animals help to enhance their hydrophobicity. The combination of geometrically textured surface and the hydrophobic nature prevents soil from sticking to the body surfaces of soil animals.

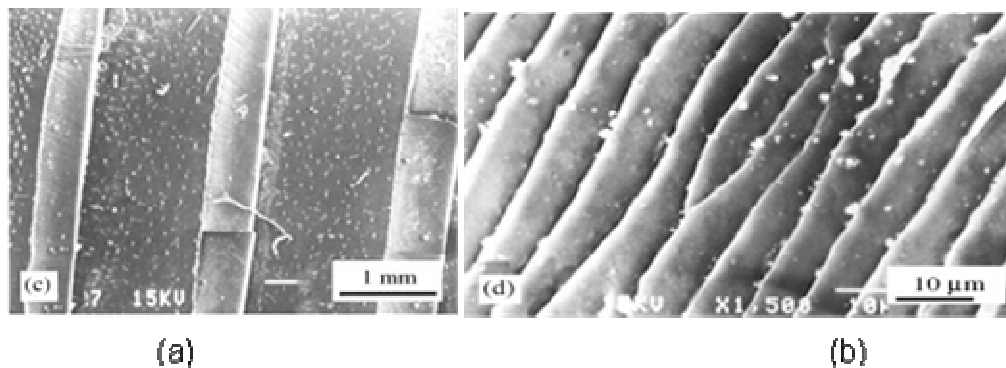
The locomotion of some organisms like caterpillar and earthworm is crawling by reversing the direction of normal peristaltic wave. Brackenbury (1999) conducted some researches on the crawling movement characteristics of such animals. He described the reverse gaits available to caterpillars and Figure 5 gives the forward movement procedure. The caterpillar and earthworm movement inspired Yao et al. (2001) into designing a push-pull air-cushioned platform vehicle. Two symmetrical air-cushioned platforms with a crawling mechanism were designed. The two air-cushioned sub-platforms with a grabbing mechanism were linked with one hydraulic cylinder. The alternating movement can be produced through the pushing and pulling operation of the hydraulic cylinder. This movement is discontinuous. The push-pull air-cushioned platform vehicle can turn around forward, backward, left or right (Moayad, 2004).

The legs and tarsal of the mole cricket and the claws and toes of the house mouse and yellow mouse have such functions as grasping, walking, clinging, and

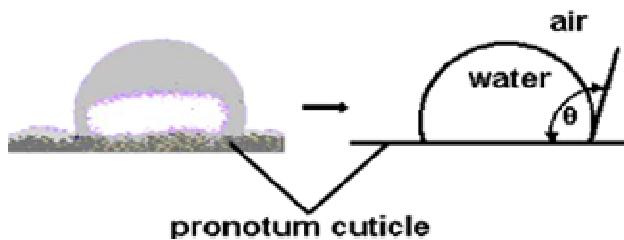


**Figure 2.** Photographs of four beetles showing the textured surface structures.

- (a) *Trachypachuslevini* (location: Oregon, USA).  
 (b) *Eustra japonica* (Location, Japan).  
 (c) *Omoglymmius hamatus* (wrinkled bark beetles. Location, California, USA).  
 (d) *Arrowina anguliceps* (Location: South India).



**Figure 3.** The textured morphologies with  
 (a) Ridged surface structure on the abdomen of a ground beetle.  
 (b) Stepped surface structure on the head of a black ant (Tong et al., 1994).



**Figure 4.** Hydrophobic nature of the pronotum cuticle surface of the dung beetle (*Coprins ochus Motschulsky*) (Tong et al., 2004).

particularly, digging. The house mouse and yellow mouse are soil-burrowing animals with strong digging claws. House mouse and yellow mouse can use their toes to

excavate. A quantitative understanding of the curvature characteristics of digging tarsal or toes of soil-burrowing animals is very useful to the biomimetic designs of soil-cutting tools like subsoilers, moldboard ploughs and furrow openers. The curvature variation of the soil-contacting surfaces of the soil-engaging components is an important factor affecting the forward resistance and working quality of the components (Tong et al., 2004).

#### Soil-tool interface

During soil-tool interaction, soil on the tool surface results in the pressure transmitted across the interface and the reaction force is closely related to the weight and type of soil. If the interface is not horizontal, then the reaction force is made up of many components. The main forces

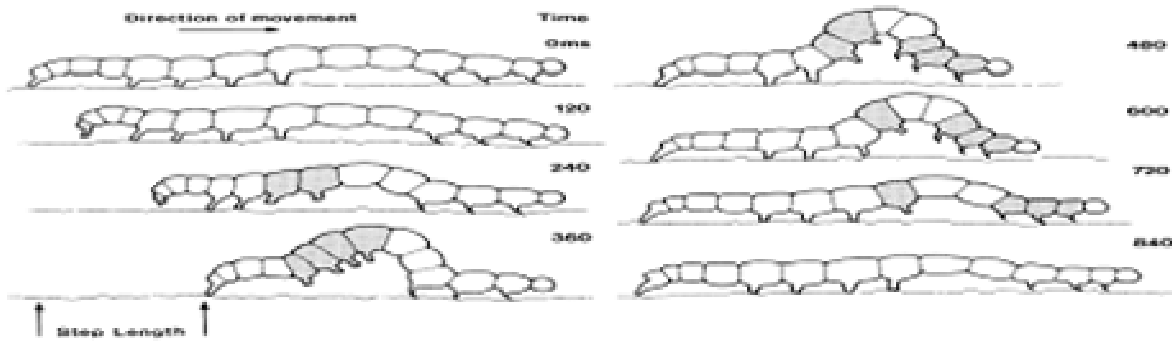


Figure 5. Forward movement in early instar of *Cucullia verbasc*. (Brackenbury, 1999)

at the interface include adhesion and friction forces which result in wear of the tool. In some cases these effects (adhesion, friction and wear) are very large, quite complex and greatly influence the interaction between soil and tool (Rabinowicz, 1995). Greenwood and Johnson (1998) suggested models for contact and adhesion of rubber. They concluded that there was a linear relationship between adhesion and size of contact area. Ren et al. (2001) investigated the effect of moisture on the adhesion forces. He found that when the moisture content of soil or its normal stress was high, the contact interface was filled with water and the soil was linked to the solid surface by a continuous water film. Moreover, soil adhesion increased with soil water tension and adhesion was also highest between the plastic limit and liquid limit. Jia (2004) concluded that the adhesion force of soil to solid materials mainly consists of intermolecular force between soil and solid, and the attraction force of the water film, which depends on the interface state of the soil and solid material. In order to see the effect of different animal body surfaces on adhesion, many researchers scanned burrowing animals using scanning electron microscope and their characteristics which enable them to overcome these problems were investigated.

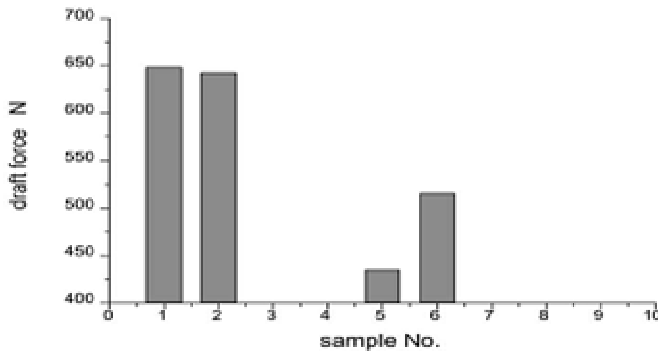
### Application of non-smooth structures in implement design

Non-smooth structures have been the most commonly used biomimetic anti-adhesion and anti-friction technique compared to others such as biomimetic electro-osmosis and biomimetic flexible structures. This could be explained by its simplicity in application compared to the other techniques.

Ren et al. (1995a) applied the concept of pseudo-variable approximation D-optimum theory to design biomimetic non-smooth surfaces of bulldozer plates based on the angle of cut, depth of cut, forward speed and soil particle size distribution. He imitated the surface morpho-

logy of the head of a dung beetle (*Ohthophagus lenzii harold*). On average, the sliding resistance was reduced by 13.2% compared to conventional plate. 18.02% was the maximum reached. The parameters used for designing the convex domes used in the best biomimetic plate were 7 mm in height, 25 mm in base diameter, a quantity of 45, and parallelogram arrangement. Ren et al. (1995b) used a statistical distribution derived by Li et al. (1995), which said that statistical position distribution of domes on a dung beetle followed a uniform statistical distribution governed by the equation  $N_L = -0.243 + 0.1692 L$ , and the base diameter of the domes which ranged from 0.033 to 0.749 mm followed a Gaussian distribution on the basis of the  $\chi^2$  test. Ren et al. (1995b) then used plain carbon steel to make the convex domes arranged on a bulldozer blade, which were tested on clay soil with a moisture content of 27% d.b and a speed of 13.33 - 58.82 mm/s. The resistance was lowered at all the speeds, but a more significant reduction was recorded at the highest speeds. Ren et al. (2003) tested different biomimetic blades with small convex domes that were different in quantity, base diameter, height and arrangement. The soil moisture content was 28.25% (d.b.) and the plastic limit and liquid limit were 22.62 and 36.33% respectively. He found that the sample with the largest convex dome base was the most effective in reducing soil resistance, 32.9% was the highest reached (sample number 5 in Figure 6). Sample 5 had 16 regularly arranged convex domes with base diameter 40 mm, height 4 mm and a distance between convex dome centres of 50 mm. The draft force of the smooth sample increased significantly as the experimental times increased, but the draft force of the non-smooth sample increased steadily, signifying that the soil which stuck on the smooth bulldozer plate helped increase the draft power (Figure 7).

Vander Straeten et al. (2004) used 10 plates with domes and dips ranging from 3 to 32 mm in height and 3 to 8 mm in depth respectively, and the arrangement was either hexagonal or parallelogram pattern covering

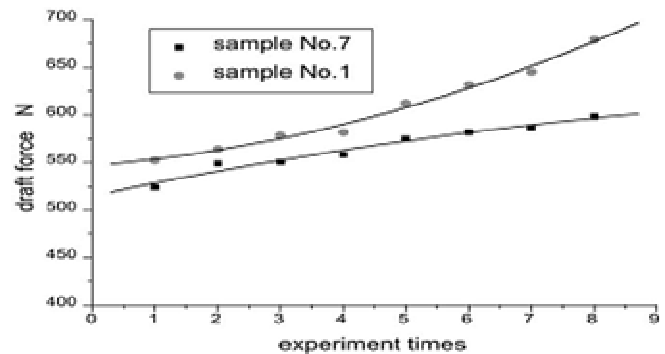


**Figure 6.** Effect of convex dome base diameter on draft force (Ren L et al, 2003).

\*Diameters are as follows: Sample 1 was smooth, sample 2 = 30 mm, sample, sample 5 = 40 mm, sample 6 = 20 mm.

between 43 and 66% of the plate area. He found that hexagonal distribution of convex domes reduced the work per surface unit by 18.5%, twice the reduction of the parallelogram distribution. He even went on to conclude that a hexagonal distribution pattern of small diameter domes and hollows at high density can substantially reduce the sliding resistance. Although he concluded that the sliding resistance of soil is mainly influenced by type of soil, type and arrangement of non smooth structures, he also confirmed that overall his results were in disagreement with already established results especially by Ren et al. (1995a). The disagreement was mainly in the best design of the non-smooth structure and extent to which sliding resistance was reduced. However, Vander Straeten et al. (2004) used loamy soils with a moisture content of 5% and a particle distribution of 20% clay, 70% silt and 10% sand whilst Ren et al. (1995a) used clay soil with an average moisture content of 27.8% (db). This makes simple comparison of any results very difficult.

Work on bulldozer blades was also done by Qaisrani et al. (1993). He used steel-45 and ultra high molecular weight polyethylene (UHMWPE) to design biomimetic blades with convex domes. Six arrangement patterns used are shown in Figure 8. The parameters used were depth of cut 15 mm, speeds of cut 0.01, 0.02 and 0.06 m/s, angle of cut 35°. From the results, he concluded that UHMWPE was more superior to steel in reducing soil resistance with the best results of 34.0 and 15.55% at the highest speed of 0.06 m/s respectively. The resistance of the other biomimetic blades made of steel-45 convex domes was even higher than that of the conventional blade. To explain behavior of UHMWPE compared to steel, Tong et al. (1999) suggested that most polymer materials, such as ultra high molecular weight polyethylene (UHMWPE) and poly tetrafluoro ethylene (PTFE,



**Figure 7.** Relationship between draft forces and experimental times for two samples (Ren L et al, 2003).

\*Sample number 1 was smooth and sample number 7 was non-smooth.

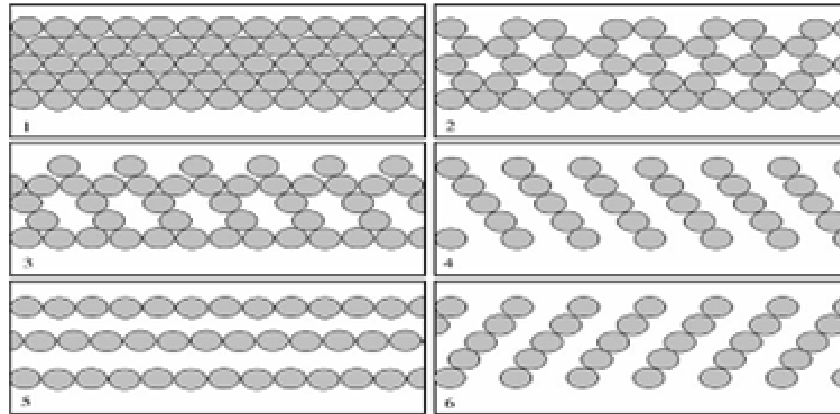
Teflon), possess lower adhesion force and friction force in soil because of their lower surface energy and higher hydrophobicity compared to steel. However, polymers have lower abrasive wear resistance especially against sandy soil hence they are not commonly used in making soil engaging equipment compared to steel.

### Explanation for inconsistency in results

The main factors affecting soil adhesion include the nature and properties of the soil, the properties of the soil-engaging component surfaces and the experimental conditions. Soil factors affecting the soil adhesion include the soil texture, moisture content, water tension, porosity and organic matter content. The soil adhesion tends to increase as the proportion of clay particles in the soil increases and is highest when the soil moisture content is between the plastic limit and the liquid limit. An increase in the soil water tension elevates the soil adhesion. The geometry and material of the domes and dips are also critical in determining the accuracy of the results. All these factors make comparison very difficult and could be the cause for inconsistency of the results cited above.

It should be emphasized that when applying the concept of non-smooth surfaces in bionic implement design, the general factors considered in arranging non-smooth structures are distribution of normal stresses, choice of material for non-smooth structures, soil motion tracks and type of non-smooth structures (Ren et al., 2004). All this is captured by carrying out the following crucial analyses (Wilson and Andrea, 2004)

**Functional analysis:** The study of the natural systems physiology, including the functional mechanisms of the



**Figure 8.** Schematic diagrams showing six regular distribution patterns of convex domes on biomimetic embossed non-smooth bulldozing blades (Qaisrani, 1993).

natural element and the principles that trigger its bio-mechanics. Among the relevant questions are: what is the function? What is it for? How does its functional system work?

**Morphological analysis:** The goal is to understand why the sample has a specific form, study the existence of geometric relationships and to observe and comprehend the texture of the sample.

**Structural analysis:** Aims at studying the organization of the natural element, its constituent parts and its capacity of undergoing stress, verifying its architecture and its natural growth.

**Analysis of viability:** Aims at studying the possibility of applying the observed characteristics into the project, and carefully evaluating all the observed aspects.

## Conclusion

From past researches, it can be concluded that indeed non-smooth surfaces can reduce soil resistance however the inconsistency in the results simply means that comparison is very difficult when experiments are done under different conditions. In addition, the function or the mechanism of operation of different implements are sometimes very different from those of soil burrowing animals which means that different implements have to be uniquely designed to achieve maximum soil resistance reduction based on biomimetics and their use.

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