P22

Developing Maximum Likelihood Approach to Three-Dimensional Reconstruction of Musculoskeletal Structure of Invertebrate Animals Based on X-ray Micro CT Data

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1 Introduction

We here propose three-dimensional reconstruction of anatomical structures such as skeletons, tendons, and muscles in invertebrate animals based on X-ray micro computer tomography (CT) image data. For example, the green brittle star, *Ophiarachna incrassate* (Fig. 1) shows adaptive locomotion using their arms that have enormous degrees of freedom. Brittle stars change movements of each arm dependent on the external environment and situation. The brittle star use arms not only to use for locomotion but also to use capture food, and so it can move arms every direction in the sea [1]_[2]. When it is captured by a predator, it shows autotomy to escape from that. Then it rushes away from the threat using arms remained with changing movement pattern of arms. Brittle stars have no central nervous systems but have a circumoral nerve ring surrounding the mouth and radial nerve cords in each arm. This suggests that each arm is controlled autonomously decentralized. Therefore, brittle star must be one of the powerful model animals to learn autonomous decentralized system and to realize as some artificial systems like autonomous robots. Our goal of the study is to elicit control structure and control rule of movements of brittle star arms and to realize autonomous decentralized system in a robot in future.

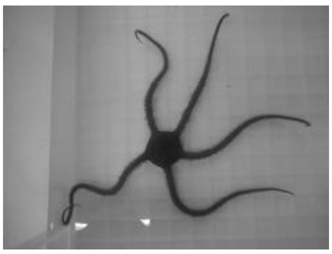


Figure 1: the green brittle star, *Ophiarachna incrassate*

2 Goal

In order to elucidate mechanisms of adaptive movements and behavior in animals and use the control structure and control rule of them to make an adaptive robot, it must be necessary to observe exact anatomical structure of animals such as vertebral ossicle and intervertebral muscles. We usually dissect animals to observe anatomical structure. Dissection makes us easy to observe fine structure of the body parts but it also makes difficult for us to understand whole structure of the body. An X-ray micro CT is one of the powerful tools to observe anatomical structure of animals. An X-ray micro-CT scanning allows us to obtain three-dimensional tomographic image of animals and allow us to observe fine anatomical structure of organs. However, until now, it has not been possible to individually extract a specific organ from a scanned image. Therefore, we here aim to extract the skeleton three-dimensionally from the tomographic image data of a brittle star. We introduced a maximum likelihood-based estimation scheme for the identification of organs, where we design the likelihood function combining the brightness distribution and the distance distribution from some specified seed points which show the outlined shapes of the organs. For this design, the contrast distributions of each organ were measured and modeled by Gaussian distributions and a novel type of distance distribution around seed points are originally introduced in the method. For verification of the proposed algorithm we also prepared the vertebral ossicle specimen of brittle star and evaluate the effectivity of the proposed algorithm experimentally.

3 Likelihoods for Segmentation in Slice

The total likelihood L_t is obtained by combining the following two likelihood functions: L_b for considering a brightness distribution and another L_d for evaluating vicinity relationship between a voxel of interest and any seed point, which are defined in Eqs.1~3.

$$L_t = L_b \times L_d \qquad (1)$$

$$L_b = \frac{1}{\sqrt{2\pi\hat{\sigma}^2}} \exp\left(-\frac{(f-\bar{x})^2}{2\hat{\sigma}^2}\right) \qquad (2)$$

$$L_d = \begin{cases} \frac{k}{d^2} & when\ \frac{k}{d^2} < 1 \\ 1 & when\ \frac{k}{d^2} \geq 1 \end{cases} \qquad (3)$$

Where f and d represents the brightness of the voxel of interest and the minimum distance from seed points respectively. The parameters $\bar{x}, \hat{\sigma}, k$ are obtained from experimental data for learning.

We manually chose some slices for providing given primary seed points (SP) and reconstructed automatically secondary

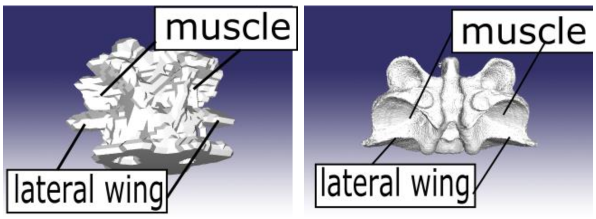
SPs for the remaining slices. Primary SPs were given to approximate a target area of organs in terms of circles at any SPs. We also defined the same number of SPs in some selected slices. A seed line (SL) was defined as a connected line segment between corresponding SPs in slices, which can deliver a set of secondary SPs on each slice enclosed by primary slices.

There were multiple identifiable organs as $w=\{w_1,w_2,\cdots,w_j\}$, the condition of the total likelihood L_t that determines that a target voxel v belongs to the organ w_j is defined by Eq.4.

$$L_{jt} = \max\{L_t\} \Leftrightarrow v \in w_j \quad (4)$$

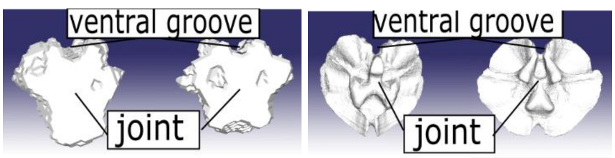
4 Comparison with Skeletal Specimen

From the results of each organ extracted from the brittle star, we used a Marching Cubes Algorithm [3] to make the surface model. About vertebral ossicle, we compared the specimen as a grand truth and the extracted shapes by the proposed algorithm. The part of the bone (lateral wing, Fig. 2) separating the four intervertebral muscles could be extracted correctly both in shape and position. Although the ventral groove in Figure 3 through which the radial nerve run though was reconstructed a little bigger than the specimen, it could express the better position and the shape. In the specimen, the joint part which has intricate structures and one of important parts in this research, is well measured in shape, but the reconstruction could not be extracted resulting a flat surface as shown in Figure 3. About the intervertebral muscles shown in Figure 4, we could reconstruct the difference in size between the dorsal side and the ventral side. About the body wall in Figure5, the three joints with the bone were found, in which the two placed on the ventral side, and the one placed on the dorsal side.



(a)algorithm (b) specimen

Figure 2: Comparison of lateral part of the bone between algorithm and specimen



(a)algorithm (b) specimen

Figure 3: Comparison of the joint part between algorithm and specimen

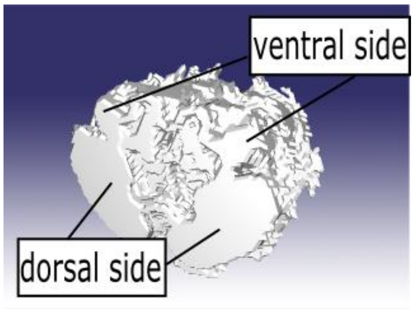


Figure 4: surface model of intervertebral muscle

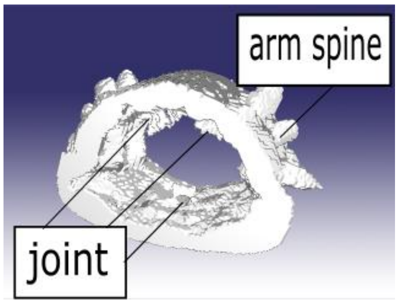


Figure 5: Surface model of the body wall

5 Summary and Future Prospects

In order to understand anatomical body structure and its function of the brittle star, we developed an algorithm to reconstruct three dimensional shapes of them from tomographic images taken with X-ray micro CT. We adopted a method of extending the likelihood for integrating the brightness distribution and the distance distribution related to seed point. As future works, we are planning to extract joints by shooting both ends of a short segment with CT along with giving regional framing for local objects. The combination of an X-ray micro CT scanning and the proposed algorithm must make us possible to reconstruct anatomical body structure and allow us better understand the functional mechanisms of animal movements.

Reference

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[3] K.S Delibasis, G.K Matsopoulos, N.A Mouravliansky, and K.S Nikita,"A novel and efficient implementation of the marching cubes algorithm", *Computerized Medical Imaging and Graphics*, Vol.25, Issue.4, pp.343-352, 2001