2D Tracking the Nuptial Dance of Platynereis Dumerilii Worms

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I. Introduction

Platynereis dumerilii are marine worms who swim when sexually mature. They reproduce through external fertilization and exhibit particular swimming behaviors during spawning. These behaviors are described as *nuptial dance* and differ based on their gender and spawning phase. Biologists want to address the hypothesis that characteristic male and female spawning behaviors are required for successful spawning and fertilization. Therefore, they want to characterize and compare male- and female-specific behaviors and analyse the spawning behaviors in a quantitative manner. To achieve this, the aim is to extract features describing their appearance (skeleton, normalized shape, curvature, etc.) and motion (trajectories of head and tail) and develop methods that enable the 2D tracking of spawning worms. See Figure 1 for an overview of the proposed approach.

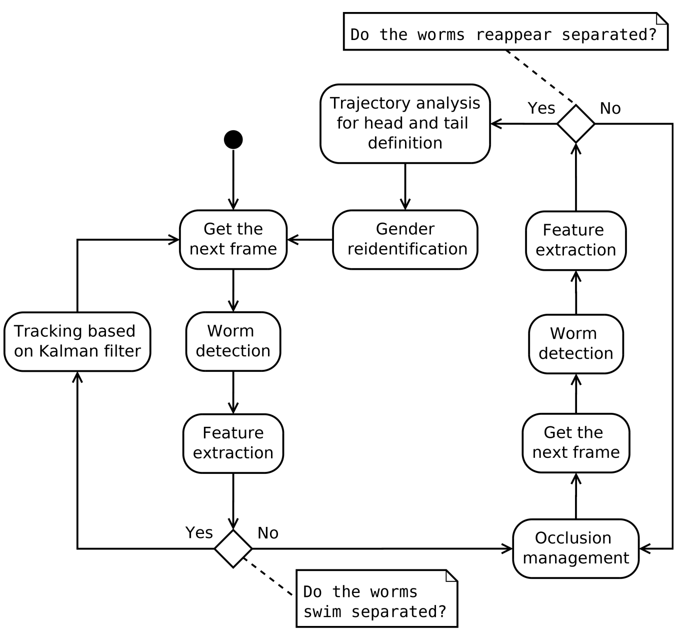

Fig. 1. Flow chart of the proposed method

A special setup is used to record the nuptial dance [2] of the worms. In nature, spawning happens around new moon in the sea at night. Therefore, the videos are recorded inside a light-tight box with an infrared camera. During the recordings, the worms are placed into a shallow, cylindrical bowl filled with sea water referred to as *arena*. The arena has a diameter of 7 cm and the average length of a worm is between 1 and 2 cm. Since the worms frequently change their motion and appearance and occlude each other when they interact, it is challenging to correctly identify the gender of the worms throughout a whole video sequence. To ensure that the collected spatio-temporal data is associated with the correct label (male or female) a combined tracking and re-identification approach is used. This gives the biologists a reliable source of information for the following analysis.

II. State of the Art

Tracking swimming worms is a challenging task, as the worms direction, speed of motion and appearance changes in a fast and unpredictable way. Husson et. at. [6] summarize a number of worm trackers focussing on single worms or on a group of worms. Background subtraction is used to track the centroids of the foreground regions. Occlusions are not handled and when two regions overlap each other, information is lost.

An approach to keep track of the worm identities while they occlude each other is described in Huang [5]. In contrast to this approach, we do not try to track the identities of the worms during occlusions, but aim to re-identify them after occlusions occur. To define the head and tail of each worm, Huang proposes a method that is based on the accumulation of fat in the head of C. elegans worms and is therefore not applicable for Platynereis dumerilii. Hoshi et. al. [4] also propose a method to detect the head and tail of C. elegans. It is based on the assumption that the head swings more than the tail, which is also not applicable to our case.

III. Normalized Shape Representation

Since worms are highly deformable, a description of their shape, which is independent of deformations, is necessary for the identification during tracking and the quantitative analysis. To achieve this, we follow a recent strategy, which is known as co-registration, where shapes are first straightened or flattened to then register different views/deformations of the same normalized shape [1]. The *normalized shape representation* is based on the skeleton (through thinning and without any branches) of the shape and the distance transform of the binary region [7].

The distance transform of the binary region holds the Euclidean distance to the nearest boundary pixel. For every point of the skeleton, the corresponding distance values hold information on the thickness of the shape. These distances also serve as radii to draw circles for the normalized shape representation. Figure 2a shows the circles of four points on the skeleton of a worm.

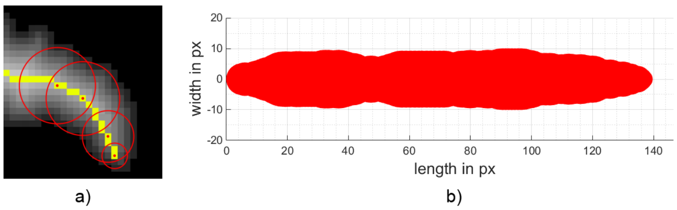

Fig. 2. (a) Four circles (red) representing the shape at four selected positions in the skeleton (red points). Yellow pixels represent the skeleton. Gray values visualize the distance to the boundary. (b) Normalized shape representation of a male worm.

A corresponding circle can be drawn for every pixel of the skeleton and the original worm shape is covert by the union of these circles. To become independent of the deformations of the worm, the skeleton points are arranged in a straight line, which gives the normalized shape (See Figure 2b). The geodesic distance along the deformed skeleton is mapped to the Euclidean distance in the normalized shape, to maintain the correspondence between deformed and normalized shape while also allowing to return to the image space.

IV. Curvature Estimation

The body curvature of a worm provides information on the swimming direction, where a mostly straight profile is indicative of linear movement while a curved body shape indicates circular movement. Furthermore, fine-scale curvatures at the tip of the tail can be used to map gamete release events on male and female worms. It is currently estimated along the worm's skeleton using a method based on osculating circles [7], since it is fast and simple to implement. Gray [3] defines the osculating circle of a curve at a given point as the circle that has the same tangent and curvature as the curve at that point. To approximate these circles on the discrete skeleton curve, circumscribed circles of triangles on the curve are used. A circumscribed circle is defined as the unique circle that passes through every vertex of a triangle. The triangles are defined for every point p_i on the skeleton and are composed of the points p_i, p_{i-k} and p_{i+k}, where the parameter k defines a neighbourhood. See Figure 3a for a visualization. The inverse of the circumscribed circle radius gives the curvature and the sign of the radius gives the direction of the curvature.

The neighbourhood k is an important factor in the accuracy of the curvature estimation. To test the accuracy, a discrete circle with a radius of 40 pixels was created with Bresenham's circle algorithm. Figure 3b shows the results. It can be observed that the error gets smaller, with increasing

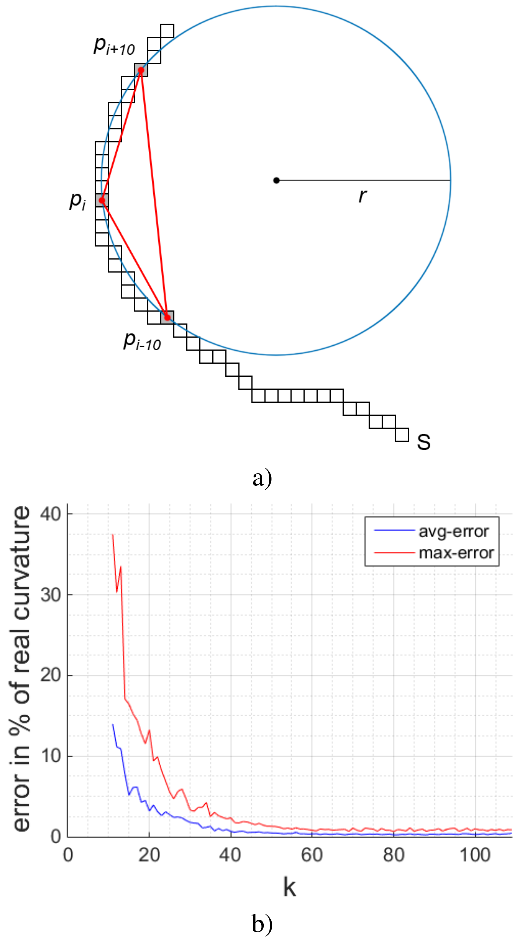

Fig. 3. (a) Illustration of the circumscribed circle (blue) for a single point p_i on a skeleton. The circle passes through every vertex of the triangle (red) formed by the points p_{i-k}, p_i and p_{i+k} with $k = 10$. (b) Plot of the avg- and max-error for the curvature estimation of a circle with radius 40 and increasing neighbourhood k.

neighbourhood k. This increased accuracy comes at a price, since small curvatures are overlooked when k is too big, which corresponds to the sampling theorem.

To address the local neighbourhood issue and increase the robustness of the curvature estimation, we are currently also working on a novel approach based on arc length propagation. Given a digital curve, individual discrete arc-segments are propagated to neighbours at increasing distances such that the arc-length remains the same along the parallel curves at these distances. For a curved sequence, the inner part will shrink forcing the arc segments to get higher weights and resulting in a local maximum. That local maximum gives the center of the best fit circle and also holds a weight corresponding to the length of the circular arc along the curve. See Figure 4 for a visualization of the general idea. With this new method we hope to achieve very robust results in contrast to other available algorithms.

Fig. 4. Propagation of arc length sequences (light green) on a given curve (gray) to find corresponding center points (dark green).

V. Worm Tracking

When the worms are swimming separately, the tracking of each worm's head and tail is done using a Kalman filter. When the worms start to interact, they occlude each other frequently in the 2D image, leading to ambiguities in segmentation and tracking. Furthermore their movement can be unpredictable, which makes continual tracking through occlusions hard. Therefore we choose to re-identify their identities after an occlusion. To do this, features of the male and female worm are collected before the occlusion to build two models. The features taken into account are currently: normalized shape (see Section III), area in pixels, mean gray-scale value of the skeleton and the length of the skeleton in pixels. A measure of similarity and majority voting are used to re-identify the worms [8].

After the re-identification, also the head and tail of each worm needs to be re-assigned. For this, the direction of the motion of the worms after the occlusion is analysed. As they tend to swim in a forward manner, the direction is a helpful cue in identifying head and tail [8].

The performance of the tracking approach has been evaluated on more than 2 hours of video material [8]. After 99.8 % of the occlusions the identity of worms was correctly re-identified. The head and tail decision was correct in 98.6 % of the cases.

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