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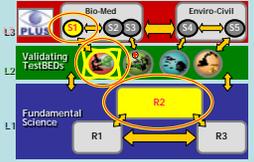
A functional model for *C. elegans* locomotory behavior analysis and its application to tracking



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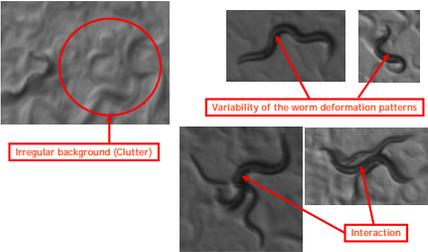
Abstract

We present a physically motivated approach to modeling the structure as well as dynamic movements of the nematode *C. elegans* as observed in time-lapse microscopy image sequences. The model provides a flexible description of a broad range of worm shapes and movements, and provides strong constraints on feasible deformation patterns to image-based segmentation, morphology, and tracking algorithms. Specifically, we model the predictable pattern of deformations of the spiral axis of the nematodes.

Model based algorithms are presented for segmentation and simultaneous tracking of an entire imaging field containing multiple worms, some of which may be interacting in complex ways. Central to our method is the observation that the spiral axis undergoes deformations obeying a pattern that can be modeled thus reducing the complexity of the measurement process from one frame to the next. Tracking is performed using a recursive Bayesian filter that performs well in the presence of clutter. Interaction between worms leads to unpredictable behaviors that are resolved using a variant of multiple-hypothesis tracking. The net result is an integrated method to understand and quantify worm interactions.

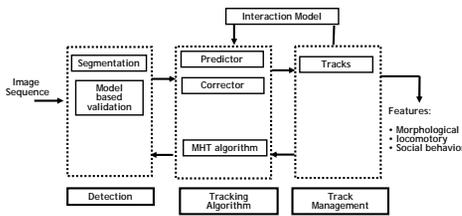
Experimental results indicate that the proposed algorithms are demonstrably robust to the presence of imaging artifacts and clutter, such as old worm tracks, in the field. An edit-based validation strategy was used to quantify the algorithm performance. Overall, the method provides the basis for high-throughput automated observation, morphology, and locomotory analysis of multiple worms in a wide field, and a new range of quantification metrics for nematode social behaviors.

Challenges



Main ideas

- Exploiting known worm locomotion concept to model movement and deformation in a correlated manner.
- Modeling interaction and overlap.
- Probabilistic approach to measurement and prediction.
- Resolving entanglement problem by a combination of Multiple hypothesis tracking and overlap modeling.



Conclusion

The proposed methods enable large scale automated analysis of entire worm populations, providing quantitative data on the morphology and locomotion of each worm. Our model can accept additional constraints on the tracking process to further improve stability and performance. Overall, our experiments indicate that our tracking algorithms are practically effective. They advance the state of the art in terms of modeling methodology, tracking performance, and analysis of multiple interacting worms. This work opens up opportunities for high-throughput locomotory analysis of worm populations, and a new range of quantification metrics for nematode social behaviors.

References

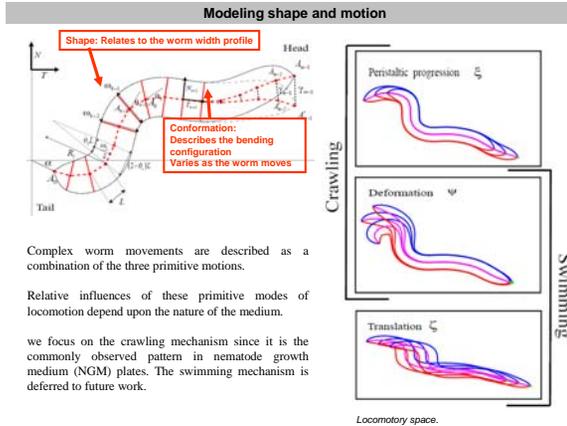
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Modeling Shape and Motion

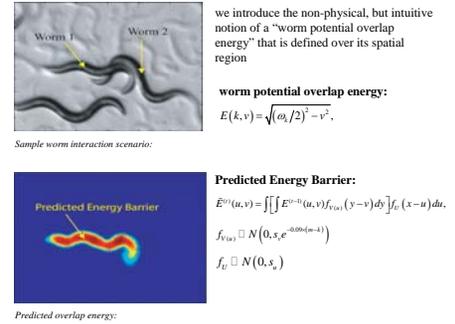


Complex worm movements are described as a combination of the three primitive motions.

Relative influences of these primitive modes of locomotion depend upon the nature of the medium.

We focus on the crawling mechanism since it is the commonly observed pattern in nematode growth medium (NGM) plates. The swimming mechanism is deferred to future work.

Physical Model for worm overlap



Tracking Framework

Probabilistic Tracking

Condensed Worm Descriptor:

$$\hat{x}_t^{(k)} = \{u_t^{(k)}, \hat{z}_t^{(k)}\}$$

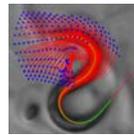
(The superscript $\{k, t\}$ describes the template to which the curvilinear translation and deformation are applied)

Stochastic Prediction Model:

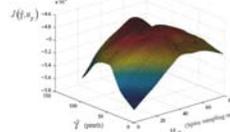
$$\begin{cases} u_t^{(k+1)} = u_t^{(k)} + w_u \\ \hat{z}_t^{(k+1)} = w_z \end{cases}$$

Measurement Model:

$$\begin{cases} J(\hat{z}, u_t) = -\sum_{i=1}^n [A_{i, \hat{z}} + \gamma_i N_{i, \hat{z}}]^2 \\ p(\hat{z}_t | \mathcal{Y}_{t-1}) = \hat{f}(\hat{z}, u_t) / J \end{cases}$$



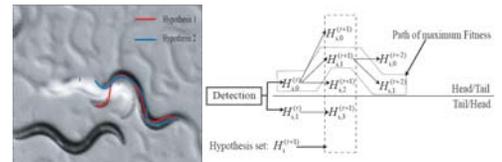
Non-linear body registration as measurement



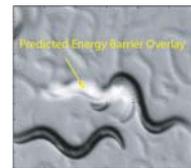
Surface plot of the state fitness estimate $J(\hat{z}, u_t)$ as a function of parameter \hat{z} and u_t .

The presence of multiple local minima can introduce some ambiguity in the measurement process. Such ambiguities occur commonly in cluttered environments and needs to be resolved through either the CONDENSATION algorithm or a multiple hypothesis tracking approach.

Resolving Worm Entanglement through multiple hypothesis tracking



Multiple-hypothesis tracking approach: At the time of detection, the tree is initialized by two nodes u_t^0 and u_t^1 , representing the uncertainty of the head location. A maximum of x local minimum of $p(x, \mathcal{Y}_t)$ could be considered as valid tracking successor for any given hypothesis. The path of maximum Fitness in the tree allows us to determine the most likely location/conformation of a worm.



Incorporating the overlap energy to the measurement process:

$$\hat{I}_1(x, y) = I(x, y) + w \left[\hat{E}_{\text{overlap}}^{(k)}(x, y) + \hat{E}^0(x, y) \right]$$

Experimental Results

Tracking output

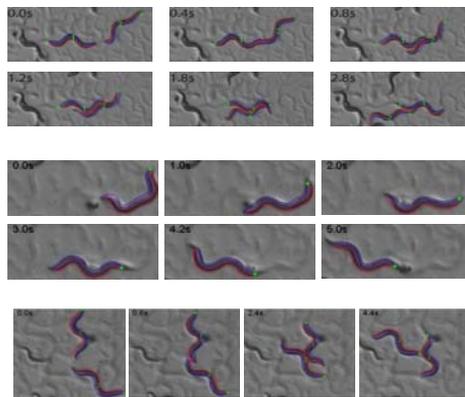
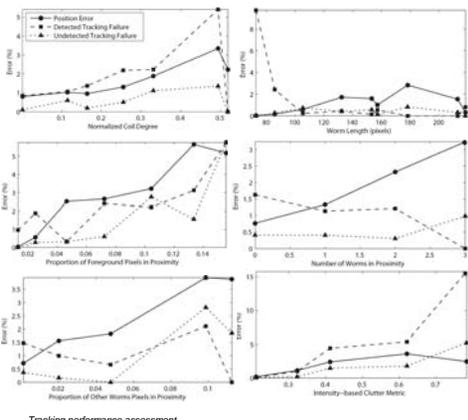


Illustration of the tracking output for several worm interaction scenario

Validation

Summary of multi-worm tracking performance data for all worms, and broken down by worm size and conformation (coiled/uncoiled). The maximal number of hypothesis per worm was set to 8x4. Severe wild-type worms were observed at 5 frames/sec over 150 frames. Our system displays excellent tracking performance even in the more difficult coiled conformations.

Worms	L2		L3		L4/Young Adult	
	Uncoiled	Coiled	Uncoiled	Coiled	Uncoiled	Coiled
Detected Tracking Failure	1.41%	7.31%	10.53%	0.49%	2.86%	0.19%
Undetected Tracking Failure	0.41%	0.00%	0.00%	0.49%	0.00%	0.48%
Normalized Segmentation Error	1.11%	0.03%	0.00%	1.07%	1.95%	1.71%
Standard Deviation	4.66%	0.76%	0.00%	4.86%	6.51%	5.15%



Tracking performance assessment.