A Lightweight Approach for Analyzing Insect Behavior on a Mobile System

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ABSTRACT

This paper describes the research, design, and development of a ligthweight system created in order to track multiple insects on just-recorded videos, and generate statistics using the obtained information. The system was created in order to replace the previous methods (manual monitoring that requires a lot of human assistance, or expensive specific instrumental) used in a laboratory to analyze insect behavior, and uses algorithms that are fast enough to allow it to run on a simple mobile phone. The final installation is simple and unexpensive, and allows the researchers to immediately obtain the data needed to evaluate their work. Typical segmentation and tracking problems (bad-quality frames, changes on the appearence of the tracked objects or the background scene, occlusion between an object and the scene or between multiple objects, or camera movement) were attacked. The tortuosity of the insect's path was calculated using our own algorithm to approximate the fractal dimension of the trails, and the result is a flexible system that allows researchers to record and immediately analyze the behavior of multiple insects in a laboratory.

Keywords

Video Processing, Object Tracking, Computer Vision, Path Tortuosity, Fractal Dimension.

1 INTRODUCTION

Starting several years ago, the increasing simplicity of access to multimedia-recording devices allowed to record high-quality videos in an almost effortless manner. This motivated the development of software applications that automatically process such information. Nowadays, not only small and cheap hardware devices can record high-quality video, but they can also process it, providing the users with very valuable data, if the right approach is taken.

We designed a system that runs on either a desktop computer, where it processes a recorded video, or in a mobile cellphone, where it also records and processes it immediatly afterwards. This replaces the previously used methods such as time consuming and error prone manual monitoring or the use of expensive specific instrumental. The system was used to test the repellent effect of some Essential Oils (*EOs*) on German cockroaches running on Petri dishes divided in zones, and analyzes several aspects on the path tracked by each roach (percentage of time spent on each zone, speed variation, and path tortuosity according to each zone).

The German cockroach, *Blattella germanica* (L.) (Dictyoptera: Blattellidae), is a recalcitrant cosmopolite pest, commonly found in houses, restaurants, schools, hospitals, and other large buildings [SH90]. These insects are a major public health concern because they are a mechanical vector of a number of human pathogenic microorganisms [FSV91] [PKC03], and they can cause allergic reactions in sensitive people [GS07]. Most control programs use chemical insecticides, and biopesticides based on EOs appear to be a complementary or alternative method for integrated pest management. Many essential oils and their constituents demonstrate insecticidal or repellent activity against the German cockroach [AGT01] [PNJC02] [TEI09] [YKY+09] [PA10] [PAS10] [ALZM11] [LYL+11]. It is known that an *EO* can provoke taxis (directed motion in response to a stimulus) and/or kinesis (undirected motion). Depending on the behavior of the insects, kinetic reactions can be classified as orthokinetic responses (changes on the speed or activity frequencies of the insects) or klinokinetics (changes on the tortuosity or direction ratio) [WGLdS+13].

This work is the result of a joint-project between the *Imaging Science Lab*, and the *Invertebrates Laboratory*, both from Universidad Nacional del Sur in Bahía Blanca, Argentina. The goal of this work was to develop an application in order to monitor the behavior of colonies of insects using the least invasive method possible, to test in turn the effectiveness of several chemicals developed by the latter group replacing the former methods in a cheap but effective way. Another contribution and potential research direction is gaining insight for the development of new bioinspired algorithms based on ant-colonies techniques. The long-term and general goal is to develop an application that allows multiple detection and tracking of generic objects.

2 RELATED WORK

Multiple object tracking is a very complex task that requires the articulation of a pipeline with several subtasks to perform adequately. It is required to initialise proper regions of interest *(ROIs)*, to identify within them the desired targets, to perform a frame-by-frame following of the identified targets, to solve unexpected situations (like crossovers, superimpositions, and jerky movements), and to extract robust information regarding the individual trajectories of the targets. Similarly, the analysis of an animal's path tortuosity is a still open area, where different movement and characterization indices are being used.

In 2004, the tortuosity of wolf paths was evaluated using (L/R^2) where L is path length and R is net displacement [WSCM04]. However, since the pixel size used to track was 25m, this method lead to huge margin errors. In addition, a probabilistic method was used to assign a goal on each of the wolves paths; in the experiments analyzed by our systems, the cockroaches have no goal and wander freely. Tortuosity is evaluated differently depending if the trail leads to an objective or not.

In 2009, a system [KT09] that performs *ROI* detection very effectively was developed. However, it requires a set of different images to use as exemplar set, and in this work, we intend to perform *ROI* detection without training (as soon as a video file has been recorded).

There are two known feature-based particle filtering object-tracking systems [SGB11] [GLLZ12] that are optimal for video-surveillance applications designed to detect and track *every* moving object. However, we must capture *only* the insects inside a region, and this approach generates problems in our videos.

Adaptive-color histogram-backprojection techniques such as the one used in [AR99] to track multiple objects in surveillance and sports videos are not robust enough, and work only on short-lenght videos (around 10 seconds), while we need to track insects for approximately half an hour (the duration of the experiments that were performed).

There is a known ant-tracking system [BKV01] created on the Carnegie Mellon University. Nevertheless, the application has several limitations and problems such as unresolved occlusion between the ants and the recipient walls, losing the track whenever two of the ants get too close together, splitting of the bounding boxes due to specular reflexes of the ants, and losing the track whenever some ant stops moving and stays in place for a long time. In addition, the system does not analyze the tortuosity of the path of the ants at all.

In a recently performed study [MCK13], which required tracking of several dozen ants, each ant had a tiny label attached to its back. While the tracking system works correctly, we had to develop a less invasive method (track each insect without physical interaction). Once again, path tortuosity was not evaluated at all in this experiment.

Regarding the analysis of an animal's path tortuosity, authors have different positions. Discrete approximation methods to evaluate fractal dimension have been used by several authors [DB88] [MCE11] [KOL]; others [Nam96], just like us, have used their own method to approximate this dimension, but rely on the same concept. Finally, some present some negative arguments about using the fractal dimension to characterize an animal's path tortuosity [HHK+04] [Ben04] [Tur96]. It is not the goal of this work to contribute to this discussion, but to reliably provide the biologists their requested results by running the system on an unexpensive platform.

By using more advanced video processing techniques, feature-detection, and with some improvements on the heuristics, we were able to eliminate or reduce drastically most of the mentioned limitations in the other systems. In addition, by using our own fast algorithm to calculate the fractal dimension of the trails, the solution provided was fast enough to run in a mobile cellphone.

3 THE APPLICATION

We designed and developed an application that processes videos performing the detection, tracking and statistical analysis of insects' trajectories running on Petri dishes. In what follows in this Section, we will describe each part of the system that implements the subtasks of the previously mentioned pipeline separately.

3.1 Videos

In the first version of our application (which runs on desktop computers), the videos were recorded by zoologists using a video camera to evaluate the repellent action of essential oils extracted from native plants from

Argentina. Paper discs of 18cm diameter were divided on two halves; one half was treated with 1ml of an essential oil, and the other remained non-treated. The paper discs were then placed inside Petri dishes, covered with 10cm plastic rings treated with vaseline to prevent the escape of the roaches. The videos were recorded during 30 minutes in closed rooms with controled moisture and temperature conditions, and were later brought to our laboratory to be processed. After improving the algorithms (specially the path tortuosity analysis) the application is now run on a mobile cellphone, which allows the researchers to record the video, analyze it, and obtain the results almost immediately (see Fig. 1).

Figure 1: The mobile version of the system, capturing video before processing it. This is all the setup required by the zoologists to test the *EOs* repellent effect.

3.2 ROI detection

In order to detect the Petri dish, which is our *Region of Interest*, a Gaussian-filtered version of the frame is obtained, using the following convolution kernel:

$$k = \frac{1}{159}\begin{pmatrix} 2 & 4 & 5 & 4 & 2 \\ 4 & 9 & 12 & 9 & 4 \\ 5 & 12 & 15 & 12 & 5 \\ 4 & 9 & 12 & 9 & 4 \\ 2 & 4 & 5 & 4 & 2 \end{pmatrix}.$$

Next, a Canny edge detection algorithm [Can86] is applied on the blurred frame: following a procedure analogous to Sobel filtering, a pair of convolution masks are applied:

$$G_{\mathrm{x}} = \begin{pmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{pmatrix}, G_{\mathrm{y}} = \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{pmatrix}$$

and the gradient strenght G and direction θ are found using:

$$G = \sqrt[2]{{G_{\mathrm{x}}}^2 + {G_{\mathrm{y}}}^2},$$

and

$$\theta = arctan\left(\frac{G_{\mathrm{y}}}{G_{\mathrm{x}}}\right),$$

rounding θ to 0, 45, 90 or 135. After applying *Non-Maximum Supression*, and with only candidate edges left, a final thresholding with hysteresis step is performed using default lower and upper threshold values (that can be modified by the program user if necessary).

Once a binary image containing the best candidate edges is obtained, a contour detection phase is performed by applying a border-following algorithm [Sb85] (which follows only the outermost borders of a binary image). After this step, only the dominant points of the curve are stored by applying the Teh-Chin chain approximation algorithm [TC89]. Finally, we decide which of the contours detected corresponds to the Petri dish by selecting the biggest contour that has a round enough shape. For efficiency reasons, (specially on the mobile version), in case of camera motion the *ROI* is repositioned semi-automatically, not frame-by-frame (the program user needs to tap the screen to do it). Fig. 2 shows the application determing the *ROI*.

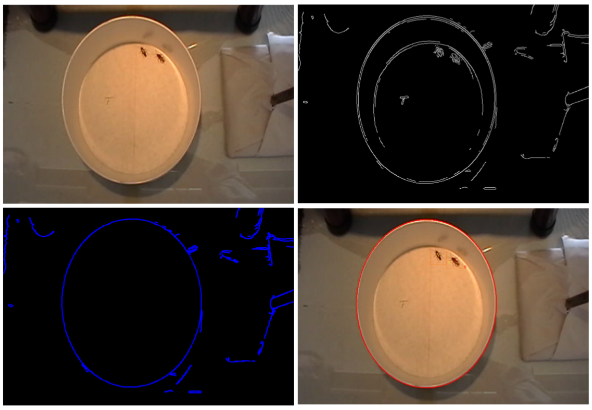

Figure 2: The ROI detection pipeline. (a) Original video frame, (b) Canny-Edge filtered frame, (c) detected contours on the Canny-Edge image, and (d) selected contour drawn on top of the original video frame.

3.3 Segmentation

This subsystem initially recognizes the roaches by applying a *k-means* clustering algorithm [Mac67] on the pixels inside the *ROI* that test positively in a comparison against a color-characteristic centroid. Given the n positive pixels inside the *ROI*, k (number of roaches in the Petri dish) clusters are obtained by: first, randomly selecting k from the n pixels; second, associating each positive pixel with the closest of the selected k pixels, resulting in a Voronoi decomposition of the n pixels; third, the centroid of each of the k clusters becomes the new *mean*, and steps two and three are repeated until the variation epsilon ε_{j_i} in the iteration i of each centroid $P_j = (X_j, Y_j)$, with $j = 1..k$:

$$\varepsilon_{j_i} = \sqrt{(X_{j_i} - X_{j_{i-1}})^2 + (Y_{j_i} - Y_{j_{i-1}})^2}$$

is small enough (in our case, $\varepsilon < 0.5$). As this is a heuristic algorithm, there is a chance it might not converge to the global optimum, depending on the initial clusters. Nevertheless, since the algorithm is fast enough (runs in polynomial smoothed complexity [AMR09]), it is run several times with different starting conditions to check the correctness of the results.

With each insect position now defined by one of the k cluster centroids, we trap each one of them inside a bounding box. From now on, every roach will be identified by using their bounding box, movement vector, and a path history that will allow us to draw the trails of each insect and calculate its tortuosity.

Due to this constraints, the system has two initialization requirements at this moment: first, the number of insects needs to be known by the program user in order to apply the *k-means* algorithm (i.e., the app is configured to segment and track k insects). Second, since a color-characteristic centroid is used, the program would not be able to track two different types of insects with a significantly different color. Nevertheless, this requirements easily fit within all the experimental settings that are performed in this biological research.

3.4 Tracking

Every frame, each pixel on a bounding box is compared against the color-characteristic centroid, capturing the movement of the characteristic pixels inside the boxes (noise is reduced using erotion/dilation techniques). Every bounding box is relocated on the new mean position of the positive pixels found (which is added to the trail history).

The occlusion problems between insects mentioned on [BKV01] are partially solved by different methods. In the paper, authors mention that when two ants get too close, the bounding boxes captured pixels from the other ants, and finally collided, losing track of one of them. In our approach, when two boxes overlap, the intersection area is ignored. By discarding the overlapping pixels, each bounding box keeps tracking only one insect. Naturally, it could occur that no positive pixels are detected due to a large overlapping area between boxes. In this case, k-means is reapplied using *every* positive pixel inside the *ROI*. The algorithm returns a new set of k points that correspond to the center of each of the colliding roaches. Since several pixels might have been discarded in previous frames due to being in overlapped boxes, the new k centroids will probably not match the registered k bounding boxes centers perfectly, and will need to be adjusted.

To decide which bounding box corresponds to each insect, a probabilistic model is used: the movement vector of each colliding roach is obtained by analyzing its recent movement history. A new hypothetical position is obtained by projecting the movement vector, and each of the bounding boxes are assigned to the free detected centroid closest to the new hypothetical position. This is a potential source of error, since certain conditions (two roaches staying in the same place, one on top of the other, for a long enough amount of time) *might* cause a bounding box swap. However, so far this didn't happen in the set of experiments already performed (and is anyways a confusion that human supervisors may also incur in). Albeit not being perfect, this tracking heuristic is still a huge improvement compared to the other insect tracking system. This part of the processing pipeline is the bottleneck that disallows the system to process the video in real-time on its mobile version: most cellphones don't have a hardware capable of capturing video and running complex algorithms on it at the same time, which is why we chose to capture the whole video (in our case, 30 minutes long), take a few minutes to analyze it, and then get the results. This limitation, however, is likely to disappear in next generation cellphones.

Another improvement in comparison to [BKV01] is that since we assume a constant amount of insects on the Petri dishes (which is how researchers performed their experiments: no insects were included in the middle of the videos), and only check for positive pixels inside of the bounding boxes, these will *never* split into several ones. The ant-tracking system analyzed the difference between frames and placed a bounding box in each cluster of positive pixels, which caused new bounding boxes to appear and track non-existent ants (which were the specular reflexion of the real ones over the Petri dish walls). The same problem occurs in the system developed by Gao *et al.* [GLLZ12]: because it is a surveillance-oriented application, their system tracks *every* moving object. In our case, the bounding boxes simply keep following the actual insects. This approach also solves the disappearing bounding boxes problem: insects are not able to "blend into the background". Fig. 3 shows the system in debugging-mode tracking two insects for several frames.

3.5 Statistical analysis

Ever since the algorithms were optimized to run on mobile phones, the statistics are obtained immediately after recording the videos. The time percentage spent on

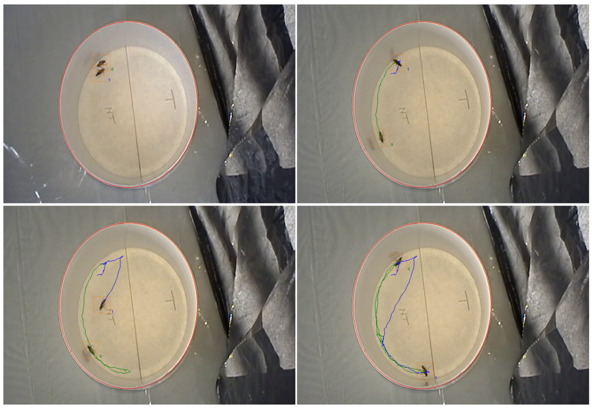

Figure 3: The system tracking two insects for several minutes. The trail left by each insect can be seen in a distinctive color.

the *EO*-treated and non-treated halves of the Petri dish is very important in order to determine if the developed insecticides are effective or not. In addition, we provide the tortuosity of the insect's trail, discriminated on each zone, so that zoologists can analyze not only if the cockroaches enter the treated zones, but also if the *EOs* modify the behavior of the roaches.

3.5.1 Permanence on each zone

Each bounding box position is checked to see whether or not an insect has trespassed to the treated area of the Petri dish. The total number of trespassings can be compared to the total number of frames to obtain the time percentage spent on each half of the Petri dish. Notice that the area definition is static, so permanence determination is affected by camera movement. However, area repositioning in case of camera movement is another easily implemented feature that will be added in future versions.

3.5.2 Tortuosity index

Because a history of the trail of each insect is stored, and a timestamp is inherently associated for a position on each frame, a tortuosity index can also be provided after the analysis for each half of the Petri dish, and for each cockroach. Trails are divided on several segments: every time a roach trespasses to the other zone of the dish, a new segment is created. This way, a set of segments tagged with a zone are obtained for each roach. Then, the tortuosity for each trail is evaluated.

One of the most common techniques to define the tortuosity of an animal's trail is to calculate an approximation to its fractal dimension. A well-known method for this is the box-counting method [FpDS99] [BKNC98] [BM01], which uses recursively smaller boxes in order to establish an exponential relationship among the boxes covered by a curve, and the side of the boxes. However, even with the optimizations created by some authors [LDS09] [BGGB98], it is still a very computationally-heavy method, and not suitable for a mobile phone on large data sets such as ours. Considering this, we had to implement a fast way to approximate the fractal dimension so that the system could run on a common smartphone.

Box-counting fractal dimension is known to converge ideally to the Hausdorff-Besicovitch self similarity dimension, which is also directly related to the dividers (or compass) dimension. Our approach, then, consists on computing an approximation of the dividers dimension using a heuristic evaluation algorithm that is fast enough even with limited processing capabilities. Each segment with at least 64 dots (which corresponds to just above two seconds of video) is analyzed. Our algorithm computes the approximation by establishing an exponential relationship among the length of the rectified trail as measured leaping every S dots, and S itself.

In other words, given a trail composed by N dots, its rectified length is measured for every stride S ranging between 1 to the length of the shortest segment (or a given maximum bound, to avoid over-calculations that are unnecessary). The length L_S of the segment is measured by averaging together the lengths computed starting on *every* dot from 0 to N mod S, and by measuring the Euclid distance every S dots until the end of the segment is reached.

$$L_S = \left(\frac{\sum_{i=0}^{NmodS} \sum_{j=S*k+i} \sqrt{(P_{\text{j}} - P_{\text{j-1}})^2}}{(NmodS)+1} \right)$$

With this L_{S} for every S, an approximation of the dividers dimension of the trail can be computed as the slope of the curve obtained by performing a quadratic regression on a point cloud formed by the points $P_S = (\log \frac{1}{S}, \log(L_s))$, for each S. Finally, and with an approximate fractal dimension for each segment, the corresponding fractal dimension of the insect's path in each half of the Petri Dish is the average of all fractal dimensions obtained for that half of the dish. Standard deviation is also calculated.

4 RESULTS

This method has been tested with a set of known fractal curves, and approximated very well to the theoretical dimension (as shown in Table 1), with the advantage of being of quadratic complexity according to the length N of each segment, which is very manageable for a mobile cellphone. The app has been (and keeps being) succesfully used to obtain hundreds of results by the zoologists. Table 2 contains the results of six experiments as an example of the application's output. In the first three, two cockroaches were placed in a Petri dish where one half was treated with Bergamot Essential Oil (2,5mg) (while the other remained untreated), and in the last three, Geranium nanoparticles were applied in the treated half. In said table, it can be observed that while the Bergamot Essential Oil did not prove to be particularly effective as a repellent on every cockroach, Geranium nanoparticles did drive the insects away during almost all the experiment. Another interesting observation is that the path tortuosity was always higher on the Geranium-treated zones than in the non treated. Full toxicological results will be published in another work.

Curve Name	Theoretical Dim.	Our result
Douady rabbit	1.3934	1.33333
Dragon curve	1.5236	1.48533
Gosper Island	1.12915	1.1955
Koch Curve	1.26186	1.27051
Minkowski sausage	1.5	1.47211
Penrose tiling	1.974	1.9199
Rauzy Fractal	1.0933	1.1111
Sierpinski	1.58496	1.51042
Terdragon curve	1.26186	1.22808
Pentaflake	1.8617	1.79787

Table 1: The theoretical dimension of some fractals, compared to the results obtained with our approach.

5 CONCLUSIONS AND FUTURE WORK

The system currently detects and tracks the insects effectively in every normal condition presented on the videos, being able to generate percentual statistics about the time spent by each roach on treated and non-treated regions of the Petri dish, and informing path tortuosity for each roach on both zones. Once the video is recorded on the phone, the program works in a fully-automatic way, except for the semi-assisted *ROI* reposition (in case the camera is moved).

The desktop version was used for several months last year, and the mobile app is being used on a daily basis to test the effectiveness of the *EOs* over dozens of videos. It has also shown robustness when abrupt changes of lightness ocurred on the room where the videos were recorded (for instance, lights were accidentaly turned on in the laboratory). The overall performance shows in general a great improvement compared to the previously known insect tracking systems. In addition, due to the relative simplicity of the tracking algorithm, the application works fast enough to track insects in real time in 1280 x 720 videos at 30 frames per second in a desktop computer, which most feature-based and complex tracking systems have serious trouble with. The mobile version waits until the video has finished recording in order to process it, to avoid processor bottlenecks (a restriction that will be likely overcome with future cellphones).

Trail	% time spent	Frac. Dim.	FD-stddev
B-T1-T	0.311621	1.213523	0.106544
B-T1-NT	0.688379	1.177511	0.101327
B-T2-T	0.293575	1.290581	0.259455
B-T2-NT	0.706425	1.1843	0.0607682
B-T3-T	0.184867	1.183575	0.150192
B-T3-NT	0.815133	1.187708	0.0620038
B-T4-T	0.215754	1.173689	0.142162
B-T4-NT	0.784246	1.176839	0.147995
B-T5-T	0.552277	1.19695	0.14304
B-T5-NT	0.447723	1.184194	0.180757
B-T6-T	0.299181	1.190842	0.159614
B-T6-NT	0.700819	1.1549	0.0783518
G-T1-T	0.021156	1.396757	0.183727
G-T1-NT	0.978844	1.249818	0.207542
G-T2-T	0.0341463	1.498832	0.22063
G-T2-NT	0.9658537	1.299669	0.116344
G-T3-T	0.00779	1.52076	0.222182
G-T3-NT	0.99221	1.182027	0.109397
G-T4-T	0.011512	1.220116	0
G-T4-NT	0.988488	1.185943	0.108329
G-T5-T	0.03029	1.312674	0.212131
G-T5-NT	0.96971	1.203907	0.137262
G-T6-T	0.069077	1.319176	0.231944
G-T6-NT	0.930923	1.20383	0.128664

Table 2: A few of the hundreds of results obtained by the app. Two different *EOs* (labeled B and G for *Bergamot* and *Geranium* were applied. Results are discriminated for each of the eight roaches, on Treated *(T)* and Not-Treated *(NT)*.

Nevertheless, the system presents some limitations. The color of the insects is defined statically, and whenever two insects occupy the same space during a large amount of time, the application may confuse them and could potentially swap the bounding boxes. Similarly, abrupt camera motion requires a user response in order to explicitely ask for a *ROI* repositioning, and makes the statistical analysis less effective.

There are several features we would like to add to the system. First of all, it would be desirable to perform the segmentation of each insect without using a characteristic color. It would also be useful to add sanity checks in order to test if the insects are effectively trapped inside their bounding boxes, and if the *ROI* is correctly positioned at some time. *ROI* tracking to detect camera motion is another possibility. Dynamic detection of the treated and non-treated areas of the Petri dish would eliminate the camera motion constraints. Adding feature-based techniques to the tracking system would make the application even more robust. Roaches collisions could be resolved in a more complex and robust way (for example, an implementation of the Minimum Cost Bipartite Matching algorithm [ADE+92]). A different clustering algorithm could be applied to check how many insects are present in the video, instead of using this knowledge beforehand to apply k-means, and finally, further optimizations could be applied to process the video in real-time on the mobile phone.

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