An autonomous robot for continuous tracking of millimetric-sized walkers

A. Serrano-Muñoz, S. Frayle-Pérez, G. Viera-López, A. Reyes, Y. Almeida, and E. Altshuler

1) Group of Complex Systems and Statistical Physics, Physics Faculty, University of Havana, 10400 Havana, Cuba
2) Faculty of Mathematics and Computer Science, University of Havana, 10400 Havana, Cuba

(Dated: 15 August 2018)

The precise and continuous tracking of millimetric-sized walkers—such as ants—is quite important in behavioral studies. However, due to technical limitations, most studies concentrate on trajectories within arenas no more than 100 times bigger than the size of the walker or longer trajectories at the expense of either accuracy or continuity. Our work describes a scientific instrument designed to push the boundaries of precise and continuous tracking up to 1000 body lengths or more. It consists of a mobile robotic platform that uses Digital Image Processing techniques to track the targets in real time by calculating their spatial position. During the experiments, all the images are stored, and afterwards processed to estimate with higher precision the path traced by the arthropods. Results achieved using the proposed tracking system are presented.

I. INTRODUCTION

Animal tracking has been a continuous challenge for scientists and engineers alike. Several approaches have been used in this field of research such as RFID, SODAR, SONAR, X-Rays, Computational Tomography and Computer Vision.

Fixed Camera tracking is the most commonly used approach to record and analyze motion of not just arthropods, but any other species or object that varies its position along time. One or more image acquiring devices are statically deployed at a given height, covering the surface to be studied. This surface is, of course, limited by the camera’s field of view. The experimental setup is quite simple and results are not affected by vibrations or displacements, given that the image acquiring device remains in the same position. However, this is a major drawback, its main disadvantage being the limitation in the area and duration of the experiments. Research efforts have been carried out using this technique to study not only single individuals, but collective motion as well. The region of study could be further increased, by raising the height of the cameras, but in doing so image resolution and therefore precision in the estimated positions may suffer substantially.

In another proposal, A. Narendra et al. mounted a differential GPS on a support that is being held by one human operator throughout their experiment. This mobile approach allows to obtain longer trajectories but the resolution of the data is low since GPS uncertainty can be as big as 1.0 cm which mostly exceeds the size of the insect body. The researchers must chase the insect, while supporting the load of the instrument. This is indeed a very labor intensive task, especially in hot temperature regions.

The work of H. Dahmen et al. stands out as an example of mobile region procedures applied to insect tracking. The instrument consists of an air-cushioned lightweight spherical treadmill that registers the path of an animal walking on top of the sphere. Long trajectories are obtained with a high degree of precision. However, this system may be considerably invasive to the insect, potentially altering its natural behavior.

In this work we aim to study single individuals in non confined areas. We have designed and implemented a system able to track millimetric-sized walkers—such as many species of insects and even crustaceans—moving over a few meters on a flat surface. This opens new possibilities in the field of behavioral ecology.

In Section II the tracking instrument is fully described. Section III presents the procedure of a typical experiment based on the proposed apparatus. In Section IV the variables being measured are described. Preliminary results based on data taken on two arthropod species are presented in Section V.

II. THE TRACKING INSTRUMENT

The complexity and hard work required to track arthropods in arenas over 1000 times larger than the size of the individual—that we will call “non-confined” areas—have led us to design an instrument that will accomplish this task in a fully automated way.

The instrument is a differential drive mobile robot able to track arthropods for long time intervals without human interaction (Figure 1). An infrared camera was placed on it in such a way that it is possible to capture images of the ground covering an area of 0.1054 m² at approximately 30 cm in front of the robot. Using an infrared camera allows the instrument to work at night which is convenient for some species. The images are scaled via GPU at 512 × 512 pixels and processed to find the position of the target individual. Decision on whether it is necessary to move the robot in order to keep the target in the field of view of the camera is made based on the position of the arthropod referred to the camera.

The electronic design of the robot was made from scratch using open source technologies. Motors with 360 steps-per-revolution hall effect encoders and a custom motor driver based on Arduino were chosen. The core of the system is the single board computer Raspberry
FIG. 1. Sketch of the instrument based on a Differential Drive mobile robot used to track non-flying arthropods. The infrared camera on top, attached at the end of the horizontal arm, allows to work on low illumination conditions. The outer diameter of the mobile robot is of 28 cm and the total length of the bar supporting the camera is of 80 cm.

Pi model 3 that handles the communications via WiFi or ethernet, the motion control and localization of the robot and the camera sampling as well as logging and optionally processing. In most cases an external computer is used to processes the images in real time in order to obtain a lower latency in the determination of further movements.

The temporal evolution of the position of the robot is stored along the images during the experiments. By processing these images it is possible to locate the walker relative to the camera. Using the information of the position of the robot in the map, it is then possible to locate the walker relative to the arena.

III. TRACKING PROCEDURE

In a previous work, several image processing tracking algorithms designed to capture the trajectory of a single insect in a sequence of frames were presented and discussed, focusing on the ones involving a mobile camera. The proposed instrument is able to work with all of them indistinctly. In this section we explain the procedure of a typical experiment, covering the details of every step of the process.

A. Work-flow

At first, the robotic platform is carried near the target individual, placing the camera right above it. At this point the trail left by the arthropod begins to be traced. The robot, and therefore the camera, remain static, hence the Frame Differencing algorithm may be applied, although other algorithms can be used. When the target moves, altering its current location, it will be detected and a Region of Interest (ROI) around it will be selected.

As it explores the arena, the walker will eventually escape the field of view of the camera. The robot must act right before this happens, rapidly moving in such a way that the target occupies again a spot near the center of the visual field of the camera, as it did at the beginning of the experiment.

Once the data from the whole experiment is gathered, the trajectory of the individual is reconstructed relative to the arena using the images and the position of the robot.

B. Real-Time Tracking

Precision is not so important at this moment, since all the frames captured by the camera and robot positions are being stored for further processing in order to obtain a highly accurate trajectory. The goal at this stage is to keep the target animal inside the field of view of the camera at all times. To accomplish this task, each frame has been divided into three regions, labeled as 1, 2 and 3 in Figure 2.

The outermost region is used as a trigger zone, to signal that the arthropod is near the edge of the field of view. The robot must then move in such a way that the target is centered. It will keep on moving in such direction, transitioning the target from the region labeled 3, to the one labeled 2 and finally 1. Once it has been positioned in this inner zone, the robot must stop and remain static, until a new escaping threat is detected, where the manner of proceeding must be the same. The radii of the circumferences enclosing regions 1 and 2 can be easily modified, as not all arthropods move at the same speed.

FIG. 2. Classification of frames in regions labeled 1, 2 and 3 based on the possibility of the target to escape from the camera’s field of view in the following frames.
C. Trajectory Reconstruction

At this point, the purpose is to obtain with the highest precision possible the actual trajectory described by the individual being tracked, despite the processing time. This can be preferably achieved once the data is gathered avoiding excessive CPU usage that may slow down the data acquisition process or allow the target to escape the field of view of the camera.

The tracking process of the individual in this stage is highly accurate, but may require human assistance in frames where the tracked object cannot be detected accurately. All the images gathered are reprocessed to acquire the position of the target arthropod referred to the camera on every frame. Next, we write the position of the arthropod relative to the arena in which the origin is the arthropod’s initial position in the ground. The problem of reconstructing the trajectory of the walker on the arena can be solved if the trajectory of the camera relative to the arena can be obtained. We implement two methods to localize the camera in order to compare the results.

The first localization method aims to estimate the camera’s position via Robot Odometry (RO). This procedure integrates the rotation of the wheels in order to compute an estimated relative location of the robot following the equations:

$$\Delta S = \frac{r}{2}(\Delta \phi_R + \Delta \phi_L)$$  \hspace{1cm} (1)

$$\Delta \Theta = \frac{r}{d}(\Delta \phi_R + \Delta \phi_L)$$  \hspace{1cm} (2)

where $\Delta S$ is the linear displacement of the robot, $\Delta \Theta$ is the angular displacement of the robot, $r$ is the radius of the wheels, $d$ is the distance between the wheels and $\Delta \phi_R$ and $\Delta \phi_L$ are the angular displacement of the right and left wheels respectively.

Based on the incremental magnitudes and the initial coordinates of the robot relative to the arena it is possible to estimate its current localization using a second order Runge-Kutta integration as shown in the following equations:

$$X_k = X_{k-1} + \Delta S \cos(\Theta_{k-1} + \frac{\Delta \Theta}{2})$$  \hspace{1cm} (3)

$$Y_k = Y_{k-1} + \Delta S \sin(\Theta_{k-1} + \frac{\Delta \Theta}{2})$$  \hspace{1cm} (4)

$$\Theta_k = \Theta_{k-1} + \Delta \Theta$$  \hspace{1cm} (5)

Since the camera is in a fixed position referred to the robot that carries it, it is possible to determine the position of the camera once the robot is localized solving Equation 6 for a given distance $(s)$ of the camera referred to the center of the robot.

$$\begin{pmatrix} X_c \\ Y_c \\ \Theta_c \end{pmatrix} = s \begin{pmatrix} \cos \Theta_r \\ \sin \Theta_r \\ 0 \end{pmatrix} + \begin{pmatrix} X_r \\ Y_r \\ \Theta_r \end{pmatrix}$$  \hspace{1cm} (6)

This method is likely to fail in conditions where the wheels may slip or the angular displacements of the wheels cannot be obtained accurately. It also carries a cumulative error due to the numerical integration.

The other approach used was the Monocular Visual Odometry (MVO). This method aims to estimate directly the position of the camera based on the detection of features on the captured images. The procedure extracts features from a first image and tries to find the same features in a second image. Afterwards, a linear transformation matrix (rotation, scale and translation) is calculated for these features. Finally, the position of the camera is estimated based on the calculated transformation matrix by a numerical integration of the relative displacements on each frame.

The scale value of the calculated matrix can be used to evaluate the quality of the computed transformation, because the scale has to be constant as the camera is not changing its height referred to the ground. In case the scale changes significantly, new features had to be acquired.

This method tracks the position of the camera directly and does not depend on the slippage of the wheels. However, it still carries a cumulative error due to the numerical integration process so it may not work depending on the amount and the quality of the tracked features.

The trajectories reconstructed with our systems are integrated with both methods and compared in order to evaluate the differences. Then, some variables of interest in the study of animal behavior are calculated from the trajectories and the differences on that variables are evaluated too.

IV. MEASURED VARIABLES

Different parameters can be used to quantify the motion of animals during free exploration, some of them have been used in very diverse fields. These parameters characterize the walker trajectory when interacting with its surroundings. For example, Escherichia coli bacteria are tracked in a three dimensional liquid solution medium, and insects such as ants in a bi-dimensional medium.

Among the parameters that influence the trajectory of the studied object are the analysis of movement diffusivity, statistics of trajectories and turn symmetries. These variables are briefly described next.

A. Statistics of runs and tumbles

Bacteria such as E. coli are well known to execute a zig-zag motion that is commonly described as “run-and-tumble.” This type of motion can be also used to describe the behavior of ants.
The term *runs* refers to the portions of the trajectory that have little or no fluctuation or angular deviation regarding the direction of the movement. *Tumbles*, on the other hand, are quasi-instantaneous turns of 90° or more referred to the previous portion of trajectory described.

**B. Diffusivity**

Diffusivity relates the average position of a particle or set of particles in a given time referred to their initial position characterized by its Mean Squared Displacement (MSD). Although most systems follow a $<x^2>$ $\sim t$ law (diffusive normal regime), there are others that exhibit the relation $<x^2>$ $\sim t^\gamma$, where the slope $\gamma$ is the parameter used to define the diffusivity. The MSD is calculated as the difference between the present position and the initial position for each instant of time. Following the classification of Viswanathan *et al.*\(^{12}\), the different regimes of motion can be classified, based in the value of $\gamma$, as super-ballistic, ballistic, super-diffusive, normal diffusive, sub-diffusive and confinement and location.

**C. Turn Symmetry**

The so-called Turn Symmetry is used to analyze the angular changes in all the trajectory. It facilitates to find turning patterns by means of a rotation histogram. To generate the data for the histograms, all angles formed by three consecutive positions are taken in account, including both runs and tumbles.

In order to analyze these variables correctly, it is necessary to obtain at all times the position of the individual with a high precision in a sufficiently long lasting experiment. Useful trajectories should be, at least, three orders of magnitude larger than the size of the individual.

**V. RESULTS AND DISCUSSION**

Several tracking experiments in non-confined regions were realized using our instrument. In this section we show results of the study of two different species: the ant *Atta insularis* and the crustacean *Armadillidium* sp., both treatable with the instrument in terms of size. Both species are shown in Figure 3. The non-confined regions covered an area of at least three orders of magnitude greater than those of the species’ bodies. Both studies were carried out in a quasi-controlled environment. The dimensions of the surface are 10 m long by 10 m wide, totaling up to 100 m\(^2\). Those of the arthropods are described in Sections **V.B** and **V.A** and are in the order of 1 cm. The area is considered non-confined. The surface over which the arthropod forages is free of obstacles and considered plane in its majority. This is a key detail regarding the direction of the movement. It facilitates to find angular changes in all the trajectory. It facilitates to find all angles formed regarding the direction of the movement. It facilitates to find all angles formed.

The trajectory was analyzed using the variables mentioned in the Section **IV.C**. The preliminary results obtained are shown in Figure 5.

It is possible to corroborate the same regime of diffusivity found by A. Reyes *et al.*\(^{13}\) for the case of confined regions.\(^{5,18–21}\) It is also possible to see that the studied variables are very consistent for both methods of camera tracking even with the cumulative errors implying a substantial difference in the trajectories. The MVO method seems to provide more accurate data in comparison to the RO method. The error in the last point of the trajectory
FIG. 5. Analysis of (a) diffusivity and (b) Turn Symmetry and Statistics of runs and tumbles for the ant Atta insularis.

was under 0.3 m in a 10 m trajectory.

B. Armadillidium sp.

Another test was performed on an isopod Armadillidium sp. Similar walkers have been studied in a 0.6 m × 0.6 m region in other works. Our experiment was performed for 11.25 min. During this interval the walker moved 19.70 m approximately. Figure 6 shows the estimated trajectory of the isopod also using both methods explained in Section III C.

FIG. 6. Estimated trajectory for the isopod Armadillidium sp. referred to its initial position using both methods of camera tracking.

The variables presented in Section IV were also computed for the case of the isopod Armadillidium sp. and the results are shown in Figure 7.

FIG. 7. Analysis of (a) diffusivity and (b) Turn Symmetry and Statistics of runs and tumbles for an individual of the species Armadillidium sp.

V. CONCLUSIONS

We have designed, constructed and tested an original autonomous robot for tracking millimetric-sized walkers, which is capable of collecting trajectories of different biological species with an uncertainty of 0.1 mm in the position of the individual within the field of view of the camera, and track it over 10 m or more, even in darkness. Even though the cumulative uncertainty in the trajectory is not greater than 0.3 m, for trajectories in excess of 10 m, this figure can be easily and substantially improved if the position of the robot can be obtained with a more accurate localization system, such as cameras deployed above the arena. Previous tracking systems typically use a fixed camera, and the walkers are followed within arenas no larger than approximately 1 meter.

We have shown the effectiveness of our robot by performing a preliminary tracking of two arthropod species: workers of the leaf-cutter ant Atta insularis and individuals of the species Armadillidium sp. The analysis of diffusivity and the run-and-tumble statistics based on the obtained tracks is consistent with previous data obtained in smaller arenas in the case of Atta insularis (analogous data for the Armadillidium sp. is not available in the literature, to our knowledge).

We believe that, by applying systematically the new tracking tool to a range of animal species, new light can be shed on long-standing biological puzzles, such as determining the precise mechanisms of orientation of millimetric-sized walkers, especially arthropods.

VI. ACKNOWLEDGEMENTS

The authors appreciate insightful discussions and data provided by M. Curbelo and A. Haidar. This work was partially supported by the University of Havana’s project “Active matter: quantification of individual and collective dynamics”.

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