



## Quantitative Analysis of Ant Motion Using Video Tracking: Evidence of Quasi-Harmonic Oscillatory Behavior

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### Abstract

The motion of living organisms, including insects, often appears irregular and complex, making it difficult to describe using simple physical models. Nevertheless, certain biological movements may contain periodic components that can be approximated using basic motion models in physics. This study aims to analyze the movement of an ant using video tracking with the Tracker software to investigate whether its motion exhibits characteristics related to simple harmonic motion (SHM). Motion data were obtained from a recorded video with a frame rate of 20 fps and processed to determine the two-dimensional position projected onto a one-dimensional displacement axis, from which velocity and acceleration were derived using Tracker. The displacement–time analysis shows quasi-periodic fluctuations that can be approximated by a sinusoidal function with an amplitude of approximately 0.042 m and a frequency of about 0.21 Hz. The acceleration–displacement relationship shows a general negative trend consistent with the tendency predicted by SHM, although deviations from ideal linearity are observed. In addition, the velocity–displacement phase diagram does not form a clear elliptical pattern, indicating that the motion does not strictly follow ideal SHM behavior. These findings suggest that ant locomotion exhibits quasi-harmonic characteristics influenced by biological locomotion mechanisms and environmental interactions, demonstrating that video-based motion analysis provides a quantitative approach for examining oscillatory components in natural biological motion.

**Keywords:** Ant motion; Video tracking; Oscillatory motion; Tracker; Quasi-harmonic motion

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## INTRODUCTION

The movement of small organisms such as insects often appears irregular because it is shaped by biological control mechanisms and continuous interactions with the surrounding environment. Even so, many forms of biological locomotion contain repetitive or rhythmic components that can be examined quantitatively. With the rapid development of digital imaging technology, video-based motion tracking has become an effective approach for investigating the trajectories of small organisms. By extracting positional data from recorded frames, researchers can obtain quantitative information on displacement, velocity, and acceleration as functions of time, thereby enabling detailed kinematic analysis of natural motion.

Recent advances in computer vision and automated tracking have significantly improved the ability to monitor insect movement. High-resolution imaging and digital tracking techniques have been used to analyze locomotion dynamics, exploratory behavior, and spatial movement patterns in various small organisms (Bochynek et al., 2017; Dell et al., 2014). More sophisticated approaches based on machine learning and deep neural networks have also been developed to track multiple ants simultaneously and examine their collective behavior under different

environmental conditions (M. Wu et al., 2022). In addition, publicly available trajectory datasets have facilitated quantitative studies of spatial and temporal movement patterns in ant colonies (M. Wu et al., 2017), while several low-cost tracking tools have expanded opportunities for behavioral studies in open environments (Sabattini et al., 2023). Despite these developments, most existing studies continue to focus primarily on behavioral classification, swarm dynamics, or ecological interactions rather than on the physical characteristics of individual trajectories from a kinematic perspective.

From a physics standpoint, motion can be described through the principles of kinematics, which examine the relationships among displacement, velocity, acceleration, and time without explicitly considering the forces that produce the motion. One fundamental example is simple harmonic motion (SHM), a form of periodic motion in which an object oscillates around an equilibrium position with a restoring tendency proportional to its displacement (Halliday et al., 2013; Serway & Jewett, 2014). In ideal SHM, displacement varies sinusoidally with time, while velocity and acceleration follow characteristic phase relationships, and acceleration is proportional to the negative displacement (Chong, 2022; B. Wu et al., 2024). These mathematical relationships provide a clear framework for testing whether an observed trajectory contains oscillatory components consistent with harmonic motion.

Although oscillatory patterns have been reported in biological locomotion, particularly in studies of inter-leg coordination in walking insects and motion tracking combined with harmonic analysis of small-organism movement (Deeti et al., 2023; Palacios-Vargas et al., 2021), explicit evaluation of whether natural trajectories exhibit characteristics comparable to SHM remains relatively limited. In particular, only a small number of studies have applied clear kinematic diagnostics, such as sinusoidal fitting, phase relationships, and the acceleration-displacement relation, to examine oscillatory components in biological motion using accessible video-analysis tools. In the context of physics education, the use of low-cost video-analysis software offers a valuable opportunity to investigate real-world motion phenomena and relate them to theoretical models through quantitative data analysis.

One widely used tool for this purpose is Tracker, an open-source video analysis and modeling software developed within the Open Source Physics project. Tracker allows users to extract positional coordinates from video frames and automatically calculate velocity and acceleration, making it possible to compare experimental motion data with theoretical kinematic models (Karuru et al., 2023; Wee & Leong, 2015). When applied to biological motion, this tool opens the possibility of exploring how natural trajectories may contain oscillatory components that can be approximated using simplified physical models while still reflecting biological variability.

The novelty of the present study lies first in its shift of focus from the predominantly behavioral and ecological description of ant locomotion toward a kinematic interpretation grounded in basic physics. While previous studies have widely used digital tracking to classify movement patterns, monitor collective behavior, or investigate spatial exploration in ants and other small organisms, limited attention has been given to whether the trajectory of an individual organism

contains oscillatory components that can be quantitatively evaluated using simple physical models. In this respect, the present study does not merely describe the path of motion, but examines the trajectory of a single ant through displacement, velocity, and acceleration data in relation to the characteristic indicators of SHM. This perspective is further supported by broader motion-analysis studies showing that the movement of living organisms can be interpreted as a structured dynamic signal rather than merely as irregular displacement patterns (Feeny et al., 2013). Accordingly, this study seeks to provide a clearer bridge between biological locomotion and introductory kinematics by testing whether natural motion may display quasi-harmonic tendencies, even when it does not fully conform to the assumptions of an ideal mechanical oscillator.

A second aspect of novelty lies in the use of Tracker as an accessible video-analysis tool to investigate quasi-periodic motion in a living organism. Although Tracker has been widely employed in physics education to analyze conventional mechanical systems, its use in biological motion studies to examine oscillatory kinematic behavior remains relatively uncommon. The present study therefore extends the pedagogical and analytical use of Tracker beyond standard textbook examples by applying sinusoidal fitting, acceleration-displacement analysis, and phase-based interpretation to an ant trajectory recorded under simple experimental conditions. In addition, image-based quantitative approaches in other domains have demonstrated that subtle oscillatory components can be extracted from recorded visual data even when they are not immediately apparent through direct observation alone (Anfinogentov & Nakariakov, 2016). Although that study was conducted in a different empirical context, it still provides methodological support for the use of video-derived motion data to investigate weak or quasi-periodic oscillatory signatures. In this way, the combination of low-cost video tracking, biologically derived motion data, and physically informed interpretation constitutes a practical and original contribution, particularly in showing how real-world motion phenomena can be connected to theoretical models in an educationally meaningful and quantitatively rigorous manner.

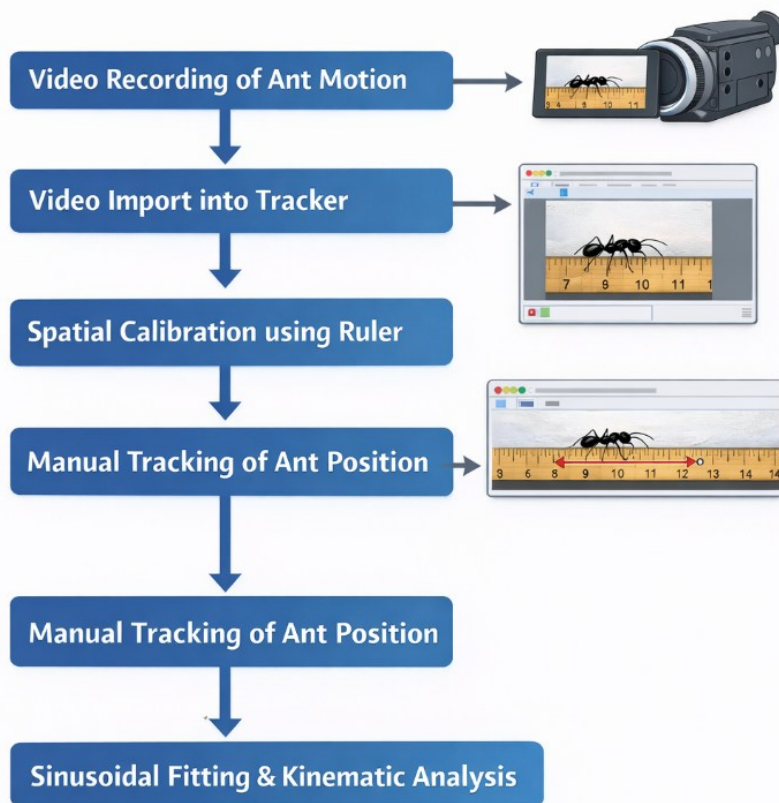
Therefore, the objective of this study is to analyze the trajectory of an individual ant using video tracking with the Tracker application in order to investigate whether its motion contains quasi-periodic components that can be approximated by a sinusoidal model related to simple harmonic motion. Through quantitative analysis of displacement, velocity, and acceleration obtained from video-tracking data, this study evaluates the extent to which the observed motion exhibits characteristics consistent with oscillatory kinematic behavior, while also acknowledging the limitations associated with biological locomotion and experimental measurement.

## **METHODS**

This study employed a video-based motion analysis approach using the Tracker application to quantitatively examine the trajectory of an ant. The experiment was conducted by observing the motion of a single ant moving freely on a flat surface. The observation focused on a short trajectory segment that exhibited noticeable fluctuations in displacement over time, allowing the motion to be examined for possible oscillatory characteristics. The analysis is therefore exploratory in nature and aims to demonstrate the use of video tracking for kinematic investigation of biological motion. The motion of the ant was recorded

using a smartphone camera positioned approximately 30 cm above a white A4 paper sheet that served as the observation surface. The paper background provided high contrast between the ant and the surrounding area, enabling more accurate visual tracking. A ruler was placed within the recording frame to provide a spatial reference for calibration. The camera was held fixed throughout the recording to maintain a stable field of view and minimize perspective distortion. The video was recorded at approximately 20 frames per second (fps).

The recorded video was analyzed using the Tracker software, an open-source video analysis tool developed within the Open Source Physics framework. Spatial calibration was performed by defining the known length of the ruler visible in the recording frame, allowing pixel displacement to be converted into metric units. After calibration, the position of the ant was tracked frame by frame using the manual tracking feature in Tracker by marking the approximate center of the ant's body in each frame. This procedure generated a time series of two-dimensional coordinates (x,y) representing the ant's position as a function of time. The overall stages of the research procedure are summarized in Figure 1.



**Figure 1.** Workflow of the video-based motion analysis procedure using Tracker

The position-time data obtained from Tracker were processed using the built-in Data Tool to compute velocity and acceleration as functions of time. These quantities were calculated through numerical differentiation of the displacement data with respect to time. Because numerical differentiation can amplify small tracking errors, the resulting velocity and acceleration values may contain fluctuations associated with measurement noise. To reduce the influence of frame-to-frame variations, the smoothing feature available in Tracker was applied to the displacement data prior to differentiation. The resulting kinematic quantities  $x(t)$ ,

$v(t)$ , and  $a(t)$  were exported from Tracker for further analysis. These data were then used to construct displacement-time, velocity-time, and acceleration-displacement plots in order to examine the kinematic characteristics of the observed motion. To evaluate whether the observed trajectory contains oscillatory components, the displacement-time data were analyzed using a sinusoidal curve-fitting approach. The displacement was approximated using the function

$$x(t) = A \sin(\omega t + \phi) \quad (1)$$

where  $x$  is the displacement from equilibrium,  $A$  is the amplitude,  $\omega$  is the angular frequency, and  $\phi$  is the initial phase. The fitting procedure provides estimates of the amplitude and frequency associated with the dominant oscillatory component of the motion. Additional diagnostic analysis was performed by examining the relationship between acceleration and displacement. In ideal simple harmonic motion, acceleration is proportional to the negative displacement according to

$$a(t) = -\omega^2 x(t) \quad (2)$$

Therefore, the acceleration-displacement plot was used as an indicator of whether the motion exhibits a general trend consistent with this relationship. It should be noted that the present analysis does not assume that the biological motion strictly follows ideal simple harmonic motion. Instead, the objective is to investigate whether the recorded trajectory contains quasi-periodic components that can be approximated using sinusoidal models. Any deviations from the ideal model are interpreted as consequences of biological locomotion variability, environmental interactions, and measurement uncertainty inherent in video-based motion analysis.

## RESULTS AND DISCUSSION

This study produced quantitative data on the movement of an ant obtained through video tracking using the Tracker application. The collected data include the ant's position, velocity, and acceleration as functions of time, which were subsequently analyzed to evaluate their conformity with the simple harmonic motion (SHM) model. The analysis involved plotting the position-time graph and performing curve fitting using a sinusoidal function to determine the amplitude and period parameters of the motion. Through this process, a quantitative description of the oscillatory pattern observed during the ant's movement was obtained, along with its degree of similarity to the ideal physical model.

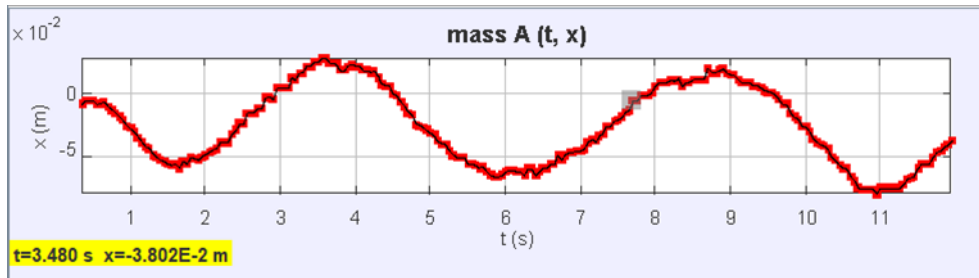
The quantitative data obtained from video tracking are presented in Table 1, showing the displacement ( $x$ ), velocity ( $v$ ), and acceleration ( $a$ ) of the ant as functions of time.

**Table 1.** Video tracking data of ant linear motion

No	t (second)	x (meter)	v (m/s)	a (m/s <sup>2</sup> )
1	4.50E-01	-4.30E-03	6.02E-02	8.00E-01
2	5.00E-01	-4.30E-03	7.69E-02	1.39E-01
3	5.50E-01	-7.74E-03	5.01E-02	3.74E-01
4	6.00E-01	-6.88E-03	9.61E-02	1.77E-01
5	6.50E-01	-6.02E-03	7.69E-02	7.67E-01
6	7.00E-01	-1.03E-02	6.55E-02	2.50E-01
7	7.50E-01	-1.20E-02	8.11E-02	5.13E-01

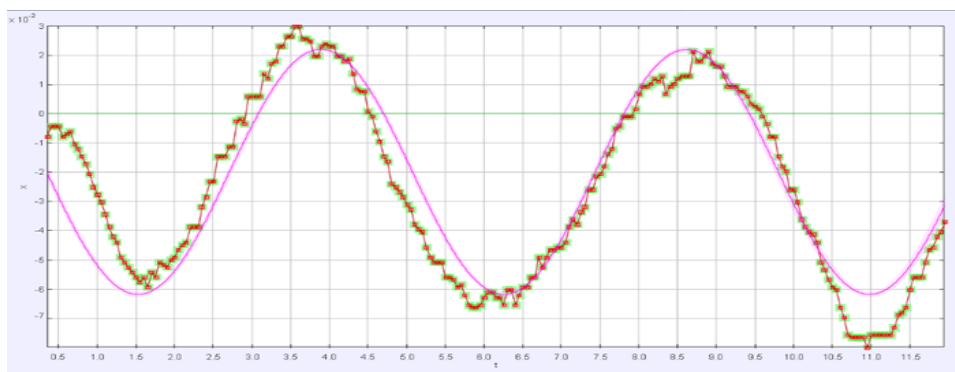
No	t (second)	x (meter)	v (m/s)	a (m/s <sup>2</sup> )
8	8.00E-01	-1.46E-02	1.00E-01	3.54E-01
9	8.50E-01	-1.72E-02	6.93E-02	8.23E-01
10	9.00E-01	-2.06E-02	7.74E-02	3.96E-01

The data in Table 1 show that while time increases uniformly, the displacement, velocity, and acceleration values exhibit fluctuating patterns. This behavior reflects the natural variability of biological motion, where the movement of the ant is influenced by internal locomotion mechanisms and interactions with the surrounding surface. To visualize the temporal pattern of motion, the displacement data were plotted against time, as presented in Figure 2.



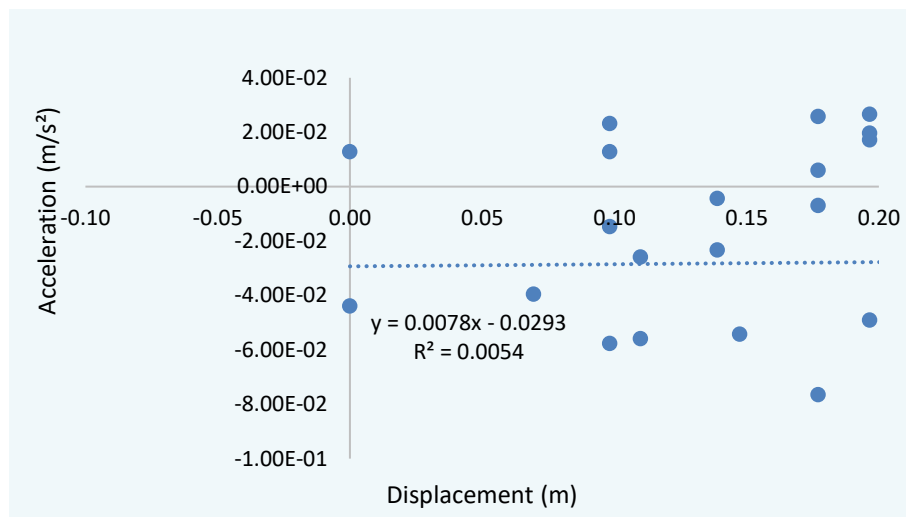
**Figure 2.** Relationship between time and the ant’s displacement

The graph in Figure 2 shows that the ant’s displacement over time exhibits a quasi-periodic pattern. Although the motion is not perfectly regular, the trajectory displays repeating fluctuations around the equilibrium position ( $x \approx 0$ ). Such behavior suggests that the movement contains oscillatory components that can be approximated using a sinusoidal function. Curve fitting using the equation (1) indicates that the motion can be described by a small-amplitude periodic model. The fitted parameters show an amplitude of approximately 0.042 m and a frequency of about 0.21 Hz, corresponding to a period of approximately 4.7 seconds. This displacement corresponds to approximately 4.2 cm, which is consistent with the spatial scale of the ant’s movement observed on the A4 paper surface during the recording. These results indicate that the ant’s motion exhibits low-frequency oscillatory behavior with small displacement variations. Similar patterns of quasi-periodic biological motion have been reported in studies of small organisms (Arroyave-Tobón et al., 2022), indicating that small-scale biological movement may exhibit periodic tendencies that can be approximated using sinusoidal functions. The sinusoidal fitting result of the present study is illustrated in Figure 3.



**Figure 3.** Sinusoidal analysis of ant movement

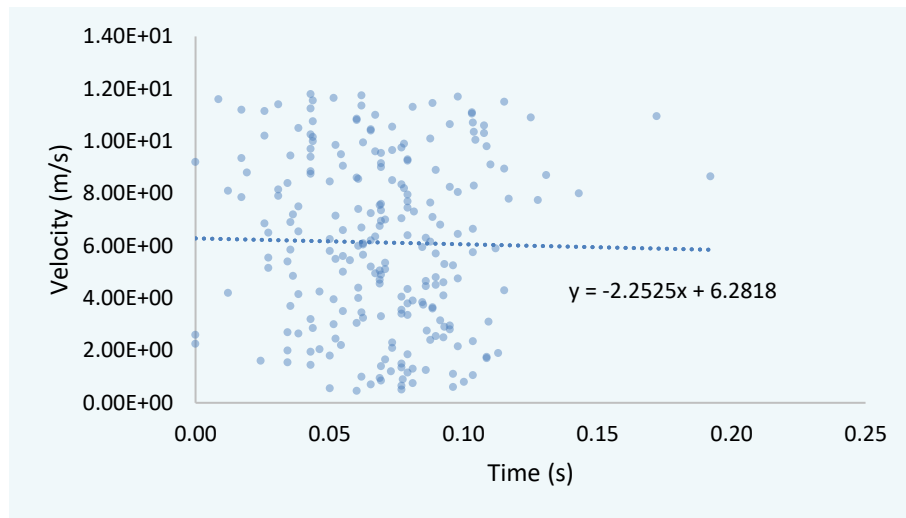
Figure 3 shows the sinusoidal curve fitting applied to the displacement data obtained from the Tracker analysis. The fitted curve follows the general trend of the experimental data, indicating that the ant's motion contains oscillatory components. Although small deviations between the fitted model and the experimental points are visible, the overall pattern suggests a quasi-periodic movement that can be reasonably approximated using a sinusoidal function. To further examine the characteristics of the observed oscillatory motion, the relationship between acceleration and displacement was analyzed. In ideal simple harmonic motion, acceleration is proportional to the displacement but acts in the opposite direction, as described in Equation (2). Figure 4 presents the acceleration-displacement plot derived from the Tracker data. The graph shows an approximately linear relationship with a negative slope, indicating that the ant's motion contains components consistent with the kinematic behavior of simple harmonic motion. However, small deviations from perfect linearity are observed, which may arise from biological variability in the ant's locomotion and environmental interactions.



**Figure 4.** Relationship between acceleration and displacement of the ant obtained from Tracker analysis.

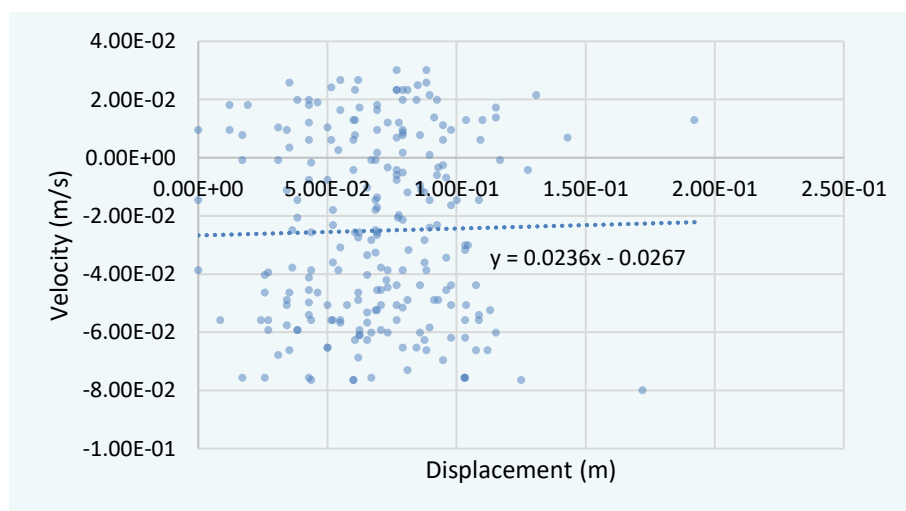
Figure 4 provides additional evidence that the ant's motion contains oscillatory characteristics. In classical simple harmonic motion, the acceleration-displacement graph forms a straight line with a negative slope equal to  $-\omega^2$ . Although the experimental data do not form a perfectly linear relationship, the overall trend still follows this theoretical expectation. The deviations observed in the data may result from several factors, including variations in the ant's walking rhythm, micro-scale surface irregularities, and limitations in video tracking precision. These factors introduce small fluctuations in the measured acceleration values, causing the scatter pattern visible in the graph. A quantitative interpretation can also be obtained from the theoretical relationship of simple harmonic motion. Based on the sinusoidal fitting results in Figure 3, the oscillation frequency of the ant's motion is approximately 0.21 Hz. Using the relation  $\omega = 2\pi f$ , the angular frequency is estimated to be about 1.32 rad/s. Consequently, the theoretical slope of the acceleration-displacement relation equation (2) is approximately  $-1.74 \text{ s}^{-2}$ . Although the experimental data in Figure 4 do not produce a perfectly linear distribution, the observed negative trend is consistent with this theoretical

expectation, indicating that the motion contains components that resemble simple harmonic behavior. To complement the kinematic analysis, the relationship between velocity and time was also examined to observe how the ant's speed varies during the recorded motion.



**Figure 5.** Velocity-time relationship of ant motion

Figure 5 presents the velocity-time relationship obtained from the Tracker data. The graph shows that the velocity values fluctuate over the observed time interval without exhibiting a consistent increasing or decreasing trend. This indicates that the ant's movement does not follow constant velocity or uniform acceleration. Instead, the speed varies from moment to moment, reflecting the natural locomotion behavior of the ant as it interacts with the surrounding surface. Such variations are common in biological motion, where organisms frequently adjust their speed and direction in response to environmental conditions. While the velocity-time graph provides information about how the ant's speed varies over time, it does not fully describe the relationship between the ant's velocity and its position during motion. To further examine the kinematic characteristics of the movement, a phase diagram was constructed by plotting velocity as a function of displacement. This relationship is presented in Figure 6.



**Figure 6.** Phase diagram of ant motion (velocity vs displacement)

Figure 6 presents the phase diagram obtained by plotting velocity against displacement using the Tracker data. In an ideal case of simple harmonic motion, the velocity-displacement relationship forms a closed elliptical trajectory in phase space. This pattern reflects the periodic exchange between kinetic and potential energy, where the velocity reaches its maximum near the equilibrium position and approaches zero at maximum displacement. In the present study, the data points do not form a clear elliptical pattern and instead appear scattered across the displacement range. This indicates that the motion of the ant does not strictly follow the characteristics of ideal simple harmonic motion. The irregular distribution of points may result from the biological nature of the ant's locomotion, where step rhythm, changes in direction, and interactions with the surface influence the instantaneous velocity and position. Therefore, although the displacement-time analysis shows quasi-periodic tendencies, the phase diagram suggests that the motion only partially resembles the kinematic behavior of simple harmonic motion.

The interpretation that the ant's trajectory may resemble simple harmonic motion (SHM) must be made with caution. The SHM model is a mechanical idealization describing oscillations under a linear restoring force, whereas an ant's movement results from the integration of neuromuscular behavior, step control, and sensory interactions with the environment. One possible origin of the observed periodic components is the step rhythm and inter-leg coupling, which in insects act as coupled oscillators, causing the center-of-mass trajectory to exhibit periodic components at certain time scales. Recent studies have shown that in walking insects, inter-leg coordination and sensory feedback control can produce consistent oscillations in the movement path like behavioral scanning or sampling, such that sinusoidal patterns in position versus time may emerge as a phenomenological manifestation of these dynamics (Deeti et al., 2023). From a physics perspective, this periodicity justifies the use of sinusoidal curve fitting to approximate motion parameters such as amplitude, frequency, and phase (Palacios-Vargas et al., 2021). Furthermore, the close agreement between experimental and fitted curves in Figure 3 supports the validity of modeling ant movement as quasi-harmonic motion, despite biological variability (Chen et al., 2021).

Environmental factors that modify the movement pattern include surface roughness, substrate gradient, visual background contrast, and the presence of chemical (pheromone) or physical stimuli. For instance, small variations in the walking surface (such as paper texture, dust, or folds) can alter step length and frequency, thereby changing the amplitude and phase of the measurable oscillation. In addition, recording conditions, such as camera frame rate, illumination, and optical stability, affect the precision of position determination in each frame, which in turn amplifies or reduces the residual deviation from the sinusoidal model. Kinematic studies at the ant scale emphasize that uncertainty propagation in motion modeling becomes more significant in small-bodied organisms; therefore, physical interpretations must account for parameter sensitivity to measurement errors (Arroyave-Tobón et al., 2022).

These findings are consistent with previous studies showing that insect movements may exhibit natural oscillatory patterns resembling simple periodic motion. Such motion can be mathematically approximated using sinusoidal models

while still considering biological and environmental variability. Previous research has also shown that digital tracking techniques are effective for analyzing micro-scale oscillatory behavior in small organisms (Eme et al., 2023; Jeyasingh-Jacob et al., 2024; Kadam et al., 2024; Provini et al., 2023). Overall, the present analysis indicates that although ant motion cannot be considered an ideal simple harmonic oscillator, its trajectory still exhibits quasi-periodic characteristics that follow the fundamental principles of simple harmonic motion, with small deviations arising from biological behavior and environmental interactions.

## CONCLUSION

This study conducted a quantitative analysis of ant motion using video tracking with the Tracker application. The results show that the displacement-time data exhibit quasi-periodic fluctuations that can be approximated by a sinusoidal function with an amplitude of approximately 0.042 m and a frequency of about 0.21 Hz. Further kinematic analysis indicates that the acceleration-displacement relationship shows a general negative trend, which is qualitatively consistent with the theoretical characteristics of simple harmonic motion (SHM). However, the phase diagram of velocity versus displacement does not form a clear elliptical pattern, suggesting that the ant's motion does not strictly follow ideal SHM behavior. Instead, the movement can be interpreted as quasi-harmonic motion influenced by biological locomotion patterns and environmental interactions. These findings demonstrate that video-tracking analysis using the Tracker application can effectively reveal oscillatory components in natural biological motion while also highlighting the limitations of applying ideal physical models to living systems. Future studies may improve measurement accuracy by employing higher-frame-rate cameras and more controlled experimental conditions to better understand the kinematic behavior of small organisms.

## RECOMMENDATION

Future studies are recommended to employ higher-resolution and high-speed cameras with stable lighting conditions to improve the accuracy of motion tracking and data extraction. More precise spatial calibration in the Tracker application is also necessary to minimize measurement errors. In addition, further investigations could involve observing multiple ants or different insect species to obtain more representative motion patterns. Improved experimental design and controlled recording environments are expected to reduce disturbances caused by uncontrolled insect behavior, video quality limitations, and environmental factors.

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