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Analysis of Parabolic Motion Trajectory Using Tracker in a Syringe Water-Jet Experiment: Potential for Child-Friendly Physics Learning

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Abstract: Projectile motion is one of the fundamental topics in physics that requires both theoretical understanding and experimental verification. However, conventional experiments may involve measurement difficulties that make it challenging to accurately observe and analyze projectile trajectories. This study aimed to analyze the projectile trajectory of a colored water jet generated by a syringe using Tracker video analysis software and to examine its potential application in physics learning. A descriptive quantitative approach was employed by recording the motion of the water jet and analyzing the recorded video frame by frame using Tracker. The trajectory data were obtained through point tracking and quadratic curve fitting to determine the characteristics of the projectile motion and its kinematic parameters. The results showed that the trajectory of the colored water jet exhibited a parabolic pattern that was generally consistent with the theoretical model of projectile motion. The use of Tracker enabled the motion to be observed and analyzed quantitatively through video, graphs, and curve fitting. The experiment also used simple and readily available materials, making it accessible for physics learning activities. These characteristics indicate that the use of Tracker with a simple water-jet experiment has potential to support accessible, engaging, and meaningful physics learning.

Keywords: Projectile motion; Tracker; Projectile motion experiment; Video-based laboratory; Kinematics

Introduction

Projectile motion is one of the fundamental topics in two-dimensional kinematics taught at both secondary school and university levels. It describes the motion of an object projected with an initial velocity at a certain angle to the horizontal, producing a characteristic parabolic trajectory under the assumption of negligible air resistance (Serway & Jewett, 2019). This motion consists of uniform motion along the horizontal axis and uniformly accelerated motion along the vertical axis due to gravitational acceleration. Understanding projectile motion is essential because it explains various physical phenomena, including the trajectories of balls in sports, water fountains, and other objects moving under the influence of gravity. Relating these theoretical principles to observable experimental phenomena remains an important aspect of physics learning.

Although the mathematical formulation of projectile motion is relatively straightforward, experimental verification is often constrained by conventional measurement techniques. Practical activities that rely on rulers and stopwatches are susceptible to human reaction time and measurement errors, potentially resulting in data that do not accurately represent the actual trajectory. Recent developments in video analysis technology have provided an alternative through Tracker, an open-source software developed within the Open Source Physics project for analyzing object motion frame by frame (Brown & Cox, 2009). By combining video recordings with spatial calibration and coordinate tracking, Tracker enables students and researchers to obtain quantitative position data that can be analyzed using graphs and curve fitting. Its application has been demonstrated in various kinematics experiments, including projectile motion, free-fall motion, oscillatory motion, and accelerated linear motion (Amoroso & Rinaudo, 2018; Prima et al., 2016; Wee et al., 2012, 2015; Renika et al., 2024; Freitas et al., 2026).

Several studies have demonstrated the potential of Tracker for improving experimental measurements and supporting physics learning. Wee et al. (2012) specifically demonstrated the use of

Tracker as a pedagogical tool for understanding projectile motion, while Afifah et al. (2015) investigated parabolic motion using Tracker as a physics learning medium. Ristiawan (2018) employed video-based laboratory techniques to analyze free-fall motion and determine gravitational acceleration. Similar applications have been reported by Tiandho (2021) and Zahran et al. (2024), demonstrating the applicability of Tracker for conducting kinematics experiments under different experimental conditions. Furthermore, Tracker has been used to investigate rolling motion (Prima et al., 2016), oscillatory motion (Amoroso & Rinaudo, 2018), and accelerated motion (Renika et al., 2024). More recent work has extended its application to the investigation of free-fall motion and vortex flows through inquiry-based experimental activities (Grimaldi et al., 2026).

Beyond its function as a measurement tool, Tracker also offers opportunities to support student-centered physics learning. Studies have reported its contribution to students' understanding of motion concepts and analytical thinking (Amaliah et al., 2020; Mardiyah & Subali, 2024; Siregar, 2024). The use of Tracker in laboratory activities has also received positive student responses (Karuru et al., 2023). Furthermore, its integration into guided inquiry worksheets provides opportunities for students to investigate physical phenomena through direct experimental observations (Muliyati et al., 2020). These findings are consistent with broader research emphasizing the importance of inquiry-based learning, authentic experimental activities, and active student engagement in science education (Dah et al., 2024; Fernandez, 2017; Gaffney, 2013; Nisa et al., 2018; Yusrizal et al., 2017). Video-based laboratory activities have also been reported to support learning outcomes, particularly when integrated with discovery learning and virtual experimental approaches (Eviota & Liangco, 2021; Fadlilah et al., 2020). The use of video analysis can also be extended to experimental investigations beyond mechanics, as demonstrated by Aguilar-Marín et al. (2018) in electricity and magnetism experiments.

Despite these developments, most previous investigations involving Tracker have focused on rigid objects, such as balls, cylinders, and other mechanical projectiles (Afifah et al., 2015; Prima et al., 2016; Wee et al., 2012, 2015). Although Tracker has also been applied to fluid-related phenomena, including vortex flows (Grimaldi et al., 2026), the quantitative analysis of a freely moving water jet as a projectile remains an interesting experimental context. A colored water jet generated by a syringe offers an alternative experimental object because it can be produced using inexpensive and readily available materials. However, unlike rigid projectiles, a water jet undergoes continuous deformation during motion, which presents additional challenges in identifying and consistently tracking its position. This characteristic provides an opportunity to investigate the applicability and limitations of video analysis techniques for studying fluid projectiles under simple laboratory conditions.

Based on these considerations, this study aims to analyze the projectile trajectory of a colored water jet generated by a syringe using Tracker software. The trajectory equation is determined through quadratic curve fitting, while the launch angle and initial velocity are estimated from the experimental data and compared with the theoretical projectile motion model. The novelty of this study lies in the application of Tracker to analyze a fluid projectile using simple and low-cost experimental equipment that can be implemented in schools and higher education institutions. This work is expected to expand the application of Video-Based Laboratory (VBL) while providing an alternative approach for conducting projectile motion experiments using readily available materials.

Methods

This study adopted a descriptive quantitative approach focusing on the experimental analysis of the projectile trajectory of a colored water jet using Tracker video analysis software. The research procedure consisted of three main stages: preparation of the experimental apparatus and materials, implementation of the projectile motion experiment, and quantitative analysis of the recorded video. Video-based analysis was employed to obtain position data from successive video frames, allowing the reconstruction and quantitative examination of the projectile trajectory. This approach follows the application of video analysis techniques in physics experiments, particularly in kinematics investigations (Brown & Cox, 2009; Wee et al.,

2012; Tiandho, 2021; Renika et al., 2024).

The use of video analysis also provides opportunities for students to investigate physical phenomena through direct observation and quantitative data interpretation. Previous studies have demonstrated the applicability of Tracker in laboratory activities and guided inquiry-based investigations (Muliyati et al., 2020; Amaliah et al., 2020). Accordingly, the present experimental procedure was designed to provide a straightforward and reproducible approach to investigating projectile motion using accessible laboratory equipment.

The materials used in this study included a syringe as the water launcher, colored water to improve the visibility of the trajectory, a ruler as a length calibration reference, a camera or smartphone for video recording, a tripod to stabilize the camera during recording, and a laptop equipped with Tracker software for motion analysis. These materials were selected because they are inexpensive, readily available, easy to operate, and suitable for conducting projectile motion experiments in laboratory and classroom environments.

The use of accessible equipment is consistent with previous investigations demonstrating that video-based experiments can be implemented using relatively simple experimental apparatus (Wee et al., 2015; Amoroso & Rinaudo, 2018; Tiandho, 2021). Furthermore, Tracker has been used in various experimental configurations to investigate mechanical motion and other physical phenomena (Aguilar-Marín et al., 2018; Prima et al., 2016; Zahran et al., 2024).

The experiment was conducted through the following steps: (1) preparing all experimental apparatus and materials; (2) filling the syringe with colored water; (3) placing the ruler within the camera's field of view as a calibration reference; (4) ejecting the water at a launch angle of approximately 30°–60° relative to the horizontal; (5) recording the projectile motion from the side with the camera positioned perpendicular to the plane of motion to minimize perspective errors; (6) importing the recorded video into the Tracker software; (7) calibrating the length scale using the Calibration Tools, defining the coordinate system with the Coordinate Axes, and setting the origin at the launch point; and (8) tracking the position of the water jet frame by frame using the Track → New → Point Mass feature to obtain the position coordinates throughout the motion.

The experimental data consisted of the position coordinates (x, y)as a function of time (t), which were automatically extracted by Tracker. The data were analyzed quantitatively using the Curve Fit feature to obtain the quadratic trajectory equation of the projectile motion. The coefficients of the fitted equation were subsequently used to determine the launch angle, initial velocity, and initial height of the water jet based on the theoretical equations of projectile motion. Finally, the experimental results were compared with the theoretical model to evaluate the agreement between the observed trajectory and the predicted projectile motion under ideal conditions.

Results and Discussion

The projectile motion of the colored water jet generated by the syringe was analyzed using the Tracker software.

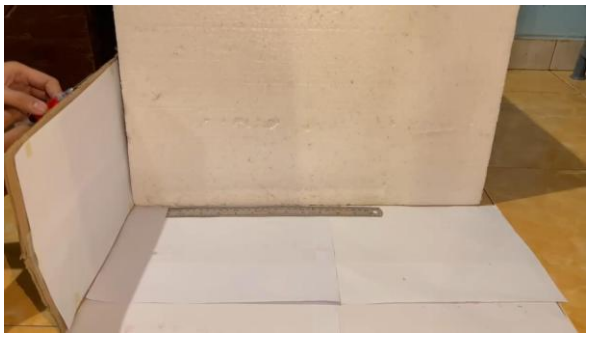

Figure 1. Experimental Setup for Projectile Motion Using a Syringe

After the calibration process and point tracking were completed, the trajectory was fitted using the quadratic regression model available in the Curve Fit feature. The resulting trajectory equation is

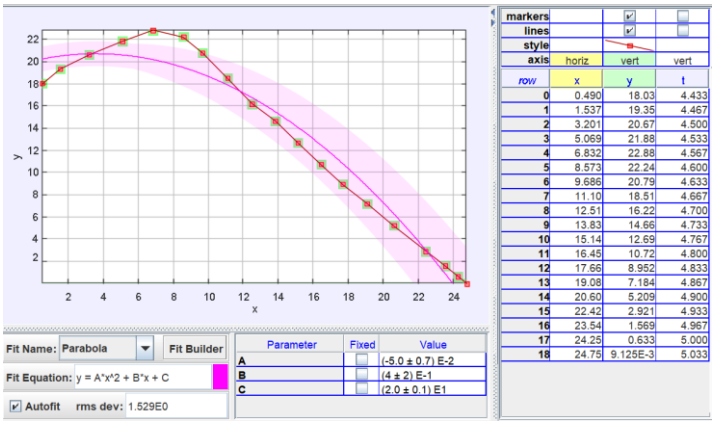

Figure 2. Projectile Motion Analysis Results Obtained Using Tracker

$$y = -0.05x^2 + 0.40x + 20.0$$

where the coefficients obtained from the fitting process are $A = (-5.0 \pm 0.7) \times 10^{-2}$, $B = (4 \pm 2) \times 10^{-1}$, and $C = (2.0 \pm 0.1) \times 10^{1}$. The fitting produced an RMS deviation of **1.529**, indicating that the quadratic function represents the experimental data with a relatively good level of agreement.

According to the theory of projectile motion, the horizontal and vertical components of motion are expressed as

$$x = v_0 \cos\theta \, t, \tag{1}$$

$$y = h_0 + v_0 \sin\theta \, t - \frac{1}{2} g t^2. \tag{2}$$

By eliminating the time variable from Eqs. (1) and (2), the theoretical trajectory equation becomes

$$y = x\tan\theta - \frac{g}{2v_0^2 \cos^2\theta} x^2 + h_0 \tag{3}$$

The experimental equation obtained from Tracker has the general form

$$y = Ax^2 + Bx + C. \tag{4}$$

The fitting coefficients are: $A = -0.05, B = 0.40, C = 20.0$. The launch angle is determined as: $\theta = \tan^{-1}(B) = 21.8°$. The initial velocity is calculated using the quadratic coefficient:

$$v_0 = \sqrt{\frac{g}{2|A|\cos^2\theta}} = 10.67 \text{ m/s}.$$

The initial height is obtained from the constant coefficient: $h_0 = 20.0$. Thus, the estimated projectile parameters are a launch angle of $21.8°$, an initial velocity of 10.67 m/s, and an initial height of 20.0 m.

Comparison Between Tracker Results and Theoretical Calculation

The comparison between the trajectory obtained from Tracker and the theoretical projectile equation shows that both have the same quadratic form. The experimental equation, $y = -0.05x^2 + 0.40x + 20.0$, is mathematically equivalent to the theoretical equation, $y = x\tan\theta - \frac{g}{2v_0^2\cos^2\theta}x^2 + h_0$, indicating that the motion of the water jet follows the fundamental characteristics of projectile motion.

The coefficient of the quadratic term obtained from Tracker is negative, confirming that the projectile experiences a constant downward acceleration due to gravity. Likewise, the positive linear

coefficient reflects the influence of the launch angle, while the constant term corresponds to the initial vertical position of the syringe nozzle. These results demonstrate that the parameters extracted from the Tracker analysis are physically consistent with the theoretical model.

Figure 2 shows that most experimental points are distributed close to the fitted parabola. However, slight deviations become apparent near the end of the trajectory, where the measured points tend to scatter around the regression curve. This behavior is reflected by the RMS deviation of 1.529, which indicates that the experimental trajectory does not perfectly coincide with the theoretical prediction.

Several factors may explain these discrepancies. The theoretical model assumes an ideal projectile moving only under the influence of gravity, whereas the experimental object was a water jet that continuously deformed into droplets during flight. This phenomenon makes the tracking point less well defined than in experiments using rigid projectiles. In addition, aerodynamic drag, manual point selection, camera perspective, calibration uncertainty, and variations in the force applied to the syringe may contribute to differences between the theoretical and experimental trajectories.

Despite these limitations, the agreement between the Tracker results and theoretical calculations is satisfactory. The fitted trajectory follows the expected parabolic pattern, while the kinematic parameters can be estimated from the regression coefficients. These findings are consistent with previous studies by Afifah et al. (2015) and Irbah and Asrizal (2019), which demonstrated the reliability of Tracker for projectile motion analysis. This study further shows that a colored water jet can serve as an alternative experimental medium for investigating projectile motion, although its shape may deform during movement.

The analysis also offers practical benefits for physics education. By combining video tracking, graphical fitting, and theoretical equations, students can connect mathematical models with observable physical phenomena. This approach supports conceptual understanding of projectile motion, particularly the relationships between launch angle, initial velocity, gravitational acceleration, and trajectory. Furthermore, Tracker enables students to practice data collection, graphical analysis, and quantitative comparison between experimental and theoretical results. Therefore, this method can be applied as an accessible and interactive learning activity in physics laboratories, helping students develop scientific reasoning and experimental data-analysis skills.

Conclusion

The results of this study indicate that the trajectory of the colored water jet produced by the syringe can be successfully analyzed using the Tracker software. The trajectory obtained from the video analysis follows a quadratic function that is consistent with the theoretical model of projectile motion. The parameters extracted from the curve fitting, including the launch angle, initial height, and initial velocity, demonstrate that Tracker is capable of providing quantitative information on projectile motion using a simple experimental setup.

A comparison between the experimental results and the theoretical calculations shows that the overall trajectory exhibits good agreement with the projectile motion model. Although slight deviations were observed between the experimental data and the theoretical curve, these differences are likely associated with several experimental factors, such as air resistance, deformation of the water jet into droplets, calibration uncertainty, and limitations in the manual tracking process. These factors are difficult to eliminate completely because the theoretical model assumes an ideal projectile moving only under the influence of gravitational acceleration.

The findings of this study support previous research demonstrating the effectiveness of Tracker as a video-based motion analysis tool for physics experiments. In contrast to earlier studies that predominantly employed solid objects as projectiles, this research utilized a colored water jet generated by a syringe. The successful analysis of the resulting trajectory indicates that Tracker can also be applied to experiments involving fluid motion, thereby extending its application to more diverse forms of projectile motion

investigations.

The implementation of Tracker in conjunction with simple and inexpensive experimental materials provides an alternative approach for conducting quantitative analyses of projectile motion in educational settings. This approach enables learners to relate theoretical equations to experimental observations through direct data analysis, while offering a practical learning experience that can be adapted to classroom activities, laboratory experiments, or independent investigations using readily available equipment.

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