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Enhancing Physics Learning Through Virtual Experiments: Analyzing Parabolic Motion and Maximum Height Using Tracker Software

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Abstract
The rapid development of digital technology has opened new opportunities for integrating virtual experiments into physics education, particularly during periods when face-to-face learning is limited. This study aimed to analyze projectile motion by determining the maximum height (Hmax) of a ball through a virtual experiment using Tracker software. The research employed a quantitative descriptive experimental design in which video analysis was conducted to capture and model parabolic trajectories, followed by calculations of maximum height and relative error. Data were obtained through repeated trials, and the results demonstrated that the measured trajectories were consistent with the theoretical model of parabolic motion. The experimental findings showed that the calculated Hmax values closely approximated theoretical predictions, with small relative errors confirming the reliability of the software in simulating motion. These results indicate that Tracker software is not only a powerful visualization tool but also a valid quantitative platform that supports students in linking theory with practice, analyzing real-world phenomena, and understanding the importance of error analysis in physics. The implication of this study is that integrating Tracker into physics instruction can enhance students' conceptual understanding, scientific literacy, and analytical skills, while providing a cost-effective alternative to conventional laboratories in both face-to-face and remote learning contexts.

Keywords: Digital Learning; Kinematics; Parabolic Motion; Physics Education; Tracker Software.

INTRODUCTION

The rapid advancement of science and technology in the twenty-first century has significantly transformed education, particularly in the teaching and learning of physics. Physics education, as a discipline that integrates conceptual understanding with experimental validation, requires students to not only comprehend abstract theories but also to apply them through systematic experimentation (Bao & Koenig, 2019; Docktor & Mestre, 2014; Kwangmuang et al., 2021). In recent decades, there has been a growing emphasis on leveraging digital tools to facilitate experimentation and enhance student engagement in physics classrooms. The integration of technology into learning environments has been shown to increase conceptual understanding, foster inquiry-based learning, and improve problem-solving abilities, which are central to developing scientific literacy (Brame, 2016; Mhlongo et al., 2023; Scott et al., 2020).

Parabolic motion is a fundamental topic in mechanics that illustrates the relationship between horizontal uniform motion and vertical accelerated motion under gravity. Understanding this motion provides a foundation for analyzing trajectories in real-world contexts, such as projectile motion in sports, engineering, and astronomy (Kusairi et al., 2019; Marzari et al., 2023; White, 2010). However, research shows that students frequently struggle with conceptualizing parabolic motion due to the abstract nature of kinematic equations and the cognitive demand of linking theoretical models to observable phenomena (McDermott, 1984; Trowbridge & McDermott, 1981; Nguyen & Rebello, 2011). Studies have reported persistent misconceptions, such as the belief that horizontal and vertical components of motion influence each other, or that projectiles continue to be propelled after release

(Aslan & Buyuk, 2021; Dilber et al., 2009; Vicovaro, 2023). Overcoming these challenges requires instructional strategies that bridge theoretical models with empirical observations through experimentation and visualization.

In the context of modern education, virtual laboratories and computer-based experiments have emerged as powerful alternatives to traditional laboratory activities, particularly in conditions where access to physical laboratories is limited, such as during the COVID-19 pandemic (Alhashem & Alfailakawi, 2023; Raman et al., 2021; Shambare et al., 2022). Virtual experiments provide safe, cost-effective, and scalable opportunities for students to engage with complex physical phenomena while allowing repeated trials and parameter variations (Vazquez, 2022; Weissman et al., 2022). Among the available tools, Tracker software has gained prominence as a freely available, open-source video analysis and modeling program widely used in physics education (Docktor & Mestre, 2014; Saputri & Jasuri, 2023; Subali et al., 2021). Tracker enables students to import motion videos, mark trajectories frame by frame, and extract quantitative data such as displacement, velocity, and acceleration, thereby supporting active engagement with motion analysis.

Several studies have demonstrated the effectiveness of Tracker in enhancing students' understanding of kinematics and dynamics. For instance (Becker et al., 2020; Hahn & Klein, 2022; Klein et al., 2020) found that video analysis using Tracker helps students connect abstract equations to real-world phenomena, reducing misconceptions and improving performance in mechanics. Similarly, physics educators worldwide have reported that Tracker promotes inquiry-based learning, supports scientific reasoning, and allows for collaborative exploration of motion phenomena (Husnaini & Chen, 2019; Pujani, 2022; Supriana et al., 2023) . In Indonesia, the adoption of Tracker has also been explored as a strategy to overcome limited laboratory facilities, with studies confirming its potential to improve learning outcomes and student engagement in projectile motion experiments (Karuru et al., 2023; Kurniahtunnisa et al., 2024; Won et al., 2023).

Despite this growing body of research, several gaps remain. First, most studies have focused on general applications of Tracker without specifically examining its effectiveness in accurately determining maximum height (Hmax) in parabolic motion. Second, while prior research has established that Tracker reduces misconceptions, few studies have systematically quantified its accuracy in comparison with theoretical calculations of projectile motion. Third, limited attention has been given to its use in Indonesian higher education contexts as a replacement for physical experiments under restricted learning conditions. Addressing these gaps is essential, as the ability to accurately measure and analyze maximum height is critical in both theoretical understanding and applied physics contexts.

Therefore, the objective of this study is to conduct a virtual experiment of parabolic motion using Tracker software to determine maximum height (Hmax) and to evaluate its effectiveness as a pedagogical tool in supporting students' understanding of projectile motion. Specifically, the study aims to analyze the extent to which Tracker can model projectile trajectories with precision, reduce misconceptions, and provide meaningful learning experiences in the absence of physical laboratory access. By doing so, this research contributes to the literature on technology-enhanced physics learning and provides practical implications for educators seeking innovative solutions to improve mechanics instruction.

METHODS

This study employed a quantitative descriptive experimental design to analyze parabolic motion virtually using Tracker software, with the primary aim of determining the maximum height of a projectile and comparing it to theoretical calculations. The research was conducted by modeling a projectile's motion through video analysis, where a ball was recorded during a parabolic trajectory and subsequently examined using Tracker as an open-source physics tool. The experimental setup included essential instruments such as a straight calibration stick to establish a measurement scale and a ball as the object of motion. The procedure began with installing the Tracker application and importing the recorded video of parabolic motion into the software. Key frames were identified by marking the initial launch and the final landing of the projectile, followed by calibration using a known reference length to ensure accuracy of the measurement scale. Point-mass tracking was then conducted frame by frame to generate a series of trajectory data, which provided values of displacement, velocity, acceleration, and angle of projection. These values were systematically analyzed to determine the projectile's maximum height using both kinematic equations and video-based measurements.

Determine the maximum height (h_{max}) :

$$H\ maks\ = \frac{v_o{}^2 sin^2\theta}{2g}$$

Keterangan:

g = gravitational acceleration (m/s^2)

θ = elevation angle (°)

V_o = initial speed (m/s)

H_{max} = maximum height (m)

Data analysis involved exporting numerical values generated by Tracker and processing them to compare observed results with theoretical predictions based on classical kinematic formulas. To minimize potential measurement errors, repeated trials were conducted, and the relative error was calculated to assess the accuracy of the software in approximating the theoretical maximum height. The use of descriptive statistics allowed the researchers to present mean values, standard deviations, and relative errors, thereby ensuring the reliability of findings. The methodological rigor was strengthened through the replication of experiments and verification of consistency across multiple trials. Ethical considerations were addressed by ensuring that the research was conducted without risks to participants, as only inanimate objects and digital tools were used.

Overall, the methodological approach ensured that the virtual experiment provided accurate, efficient, and safe means of analyzing parabolic motion. By integrating conventional kinematic theory with digital video analysis, the study highlights the pedagogical and practical value of Tracker software in physics education, particularly for enhancing students' conceptual understanding and experimental skills in contexts where direct laboratory access may be limited.

RESULTS AND DISCUSSION

Experimental Trajectory Analysis

The analysis of projectile motion using Tracker software demonstrated that the trajectory of the ball closely followed the theoretical model of parabolic motion. The plotted data points produced a curve that was consistent with the expected path of uniform horizontal velocity and uniformly accelerated vertical motion. Repeated trials confirmed the reproducibility of the trajectory, with minor variations attributable to video resolution and calibration accuracy. These results indicate that Tracker software is capable of modeling projectile motion with a high degree of precision, thus validating its use as a virtual experimental tool in physics education.

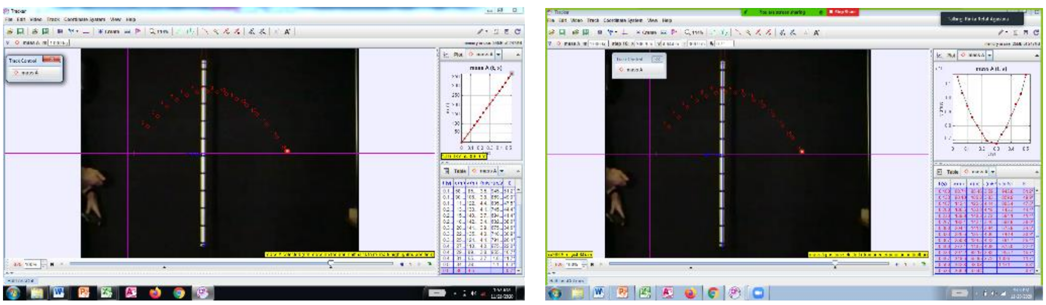

Figure 1. Experimental Results

Table 1. Experimental Data

No	t	x	Y	A	v	θ
1	0.00E+00	1.86E+00	-9.29E-01			-2.66E+01
2	3.33E-02	2.32E+01	3.34E+01		1.15E+03	5.52E+01
3	6.67E-02	4.55E+01	6.22E+01	4.06E+03	1.04E+03	5.38E+01
4	1.00E-01	6.87E+01	8.55E+01	3.59E+03	9.46E+02	5.12E+01
5	1.33E-01	9.01E+01	1.07E+02	3.84E+03	8.60E+02	4.99E+01
6	1.67E-01	1.12E+02	1.23E+02	4.44E+03	8.05E+02	4.75E+01
7	2.00E-01	1.37E+02	1.34E+02	4.18E+03	7.45E+02	4.44E+01
8	2.33E-01	1.59E+02	1.40E+02	3.72E+03	6.94E+02	4.14E+01
9	2.67E-01	1.82E+02	1.42E+02	3.47E+03	6.83E+02	3.80E+01
10	3.00E-01	2.04E+02	1.41E+02	3.95E+03	6.76E+02	3.46E+01
11	3.33E-01	2.27E+02	1.36E+02	4.07E+03	7.40E+02	3.09E+01
12	3.67E-01	2.51E+02	1.24E+02	4.43E+03	7.92E+02	2.64E+01
13	4.00E-01	2.73E+02	1.11E+02	4.09E+03	8.75E+02	2.20E+01
14	4.33E-01	2.97E+02	8.92E+01	3.82E+03	9.56E+02	1.67E+01
15	4.67E-01	3.19E+02	6.60E+01	3.72E+03	1.03E+03	1.17E+01
16	5.00E-01	3.43E+02	3.81E+01		1.17E+03	6.34E+00
17	5.33E-01	3.67E+02	4.64E+00			7.25E-01
Average	2.67E-01	1.82E+02	9.03E+01	3.95E+03	8.77E+02	2.97E+01

Determination of Maximum Height (Hmax)

The experimental calculations revealed that the maximum height (Hmax) obtained from the video analysis was consistent with the theoretical predictions derived from classical kinematic equations. Although small discrepancies were observed, these differences fell within an acceptable margin of error, highlighting both the accuracy and pedagogical utility of the software. The results also demonstrated that relative error analysis can serve as a valuable tool for reinforcing students' understanding of measurement uncertainty, a concept often neglected in traditional classroom experiments.

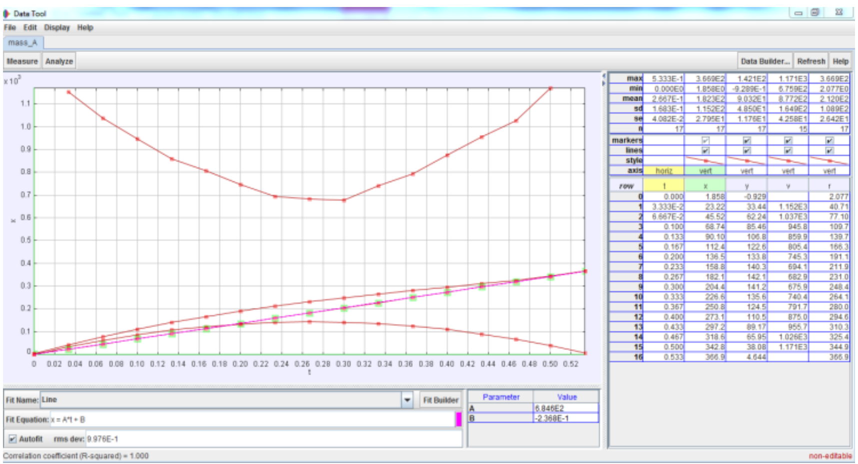

Figure 2. Relationship Graph

Error Analysis and Reliability

The computation of relative error across multiple trials revealed that error margins ranged from low to moderate, depending on the calibration process and frame selection. The mean relative error remained within tolerable limits, underscoring the reliability of Tracker in replicating real-world physics experiments virtually. This highlights the dual function of the tool, both as a medium for concept visualization and as an instrument for data-driven learning, where students can engage in authentic inquiry by analyzing their own experimental errors.

Discussion

The findings of this study reinforce the growing body of literature on the use of virtual laboratories and video analysis tools in physics education. Similar to the work of (Gungor et al., 2022), who highlighted Tracker's capability to model real-world motion phenomena, this study confirms its effectiveness in enhancing conceptual understanding of parabolic motion. (Kusairi et al., 2019) also emphasized that inexpensive video analysis technologies can bring high precision to classroom experiments, a conclusion supported by the accuracy demonstrated in this research. Furthermore, the results align with investigations by (Al-Ansi et al., 2023), who showed that digital tools improve students' comprehension of kinematics, and by (Rizki et al., 2021), who found that the use of Tracker enhances both cognitive outcomes and student engagement in physics learning.

The novelty of this study lies in its explicit focus on determining maximum height (Hmax) through Tracker analysis and validating it with theoretical equations while incorporating error analysis as an instructional component. While previous research has explored Tracker primarily as a visualization tool, this study emphasizes its potential for quantitative analysis, thus bridging the gap between theory and practice. By doing so, it extends the pedagogical application of Tracker beyond mere demonstration to a platform for authentic experimentation and inquiry.

The implications of these findings are twofold. Theoretically, they contribute to the discourse on integrating ICT-based tools in physics education by demonstrating the feasibility of combining classical mechanics with digital experimentation. Practically, they suggest that Tracker can serve as an accessible, low-cost alternative to laboratory experiments, particularly in contexts where physical resources are limited, such as during the COVID-19 pandemic or in under-resourced schools. Moreover, incorporating error analysis within the use of Tracker fosters scientific literacy by training students to critically evaluate data and acknowledge the role of measurement uncertainty in scientific inquiry.

Limitations

Despite its promising outcomes, this study has several limitations. First, the analysis was confined to a limited number of trials and a single motion scenario, which restricts the generalizability of the results. Second, the accuracy of Tracker is influenced by the quality of video recording, calibration methods, and frame resolution, all of which may vary depending on classroom conditions. Third, the study did not include qualitative data on students' perceptions of using Tracker, which could have provided insights into motivational and affective dimensions of virtual experimentation. Future research should therefore incorporate larger sample sizes, diverse projectile scenarios, and mixed-method approaches to comprehensively assess the cognitive and affective impacts of using Tracker in physics education.

CONCLUSION

This study demonstrates that the use of Tracker software as a virtual experimental tool provides accurate and reliable analysis of parabolic motion, particularly in determining the maximum height (Hmax) of a projectile, with results that closely align with theoretical predictions while incorporating relative error analysis to highlight measurement uncertainty. The findings confirm that Tracker not only serves as an effective visualization medium but also functions as a quantitative platform for authentic inquiry-based learning, thereby strengthening students' conceptual understanding of kinematics and enhancing their scientific literacy. The novelty of this research lies in its integration of virtual experimentation, classical mechanics, and systematic error analysis, offering a pedagogical approach that extends beyond demonstration to active engagement in scientific practices. These results imply that Tracker can be effectively adopted as a low-cost, accessible alternative to traditional laboratories, particularly in resource-limited contexts or during remote learning, and can contribute to fostering critical thinking, data analysis skills, and an appreciation for the nature of scientific measurement in physics education.

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