

ROBUST VIDEO TRACKING OF MULTIPLE PENDULUMS UNDER IMPERFECT LIGHTING

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This paper presents a method for robust tracking of multiple pendulums using video analysis under imperfect lighting conditions. The experimental setup consists of five pendulums recorded by a stationary camera at 30 frames per second. Object detection is performed using color-based segmentation in the HSV color space implemented in Python with the OpenCV library. Two approaches are compared: a baseline method with a non-robust color mask and an improved method with optimized masking parameters. The quality of tracking is evaluated using temporal derivatives of the detected trajectories, specifically the second-order derivative, which highlights high-frequency noise caused by unstable detection. The results show a significant reduction in noise and improved trajectory smoothness when using the optimized mask. The proposed approach provides a simple and effective solution for motion tracking in suboptimal lighting conditions.

KEYWORDS

video tracking, pendulum motion, computer vision, OpenCV, HSV segmentation, motion analysis, noise reduction

1 INTRODUCTION

The analysis of pendulum motion represents a fundamental topic in physics and engineering, commonly used to demonstrate principles of periodic motion and dynamic systems. Traditionally, such motion is measured using dedicated sensors or optical systems, which may require specialized equipment and controlled laboratory conditions.

With the increasing availability of digital cameras and computational tools, video-based motion analysis has become an accessible alternative. Computer vision techniques allow object tracking directly from video sequences without the need for physical sensors [Nowakowski 2025]. Among these techniques, color-based segmentation in the HSV color space is widely used due to its simplicity and computational efficiency [Szeliski 2010].

However, a significant limitation of such approaches is their sensitivity to lighting conditions. Variations in illumination can lead to unstable object detection, resulting in inaccurate trajectory estimation [Gonzalez 2018, Kondrat 2025]. This issue becomes more pronounced in multi-object tracking scenarios, where multiple targets must be detected simultaneously [Klette 2014].

This paper focuses on improving the robustness of video-based tracking of multiple pendulums under imperfect lighting conditions. A comparative analysis between a baseline and an optimized detection approach is presented. The quality of tracking is evaluated using temporal characteristics of the detected trajectories, enabling objective assessment of detection stability.

In recent years, video-based motion analysis has gained significant attention due to the increasing availability of low-cost imaging devices and open-source software tools [Bradski 2008]. This trend has enabled the development of accessible experimental setups that do not require specialized measurement equipment.

However, practical implementations of such systems often face challenges related to environmental conditions, particularly illumination variability. These factors can significantly affect the accuracy and reliability of object detection algorithms, especially in educational or laboratory environments where precise control of lighting is not always possible.

Beyond the technical aspects of object tracking, the presented approach is also motivated by the need for accessible tools for experimental analysis of dynamical systems [Zidek 2024]. In particular, the study of free oscillatory systems, such as pendulums, plays an important role in physics and engineering education.

Accurate trajectory extraction enables further analysis of system properties, including frequency, damping, and synchronization effects. However, in many practical scenarios, experimental conditions are not ideal, and limitations such as imperfect lighting may significantly affect measurement quality. Therefore, improving the robustness of video-based tracking is essential not only for reliable object detection, but also for enabling meaningful physical analysis of oscillatory systems.

2 MATERIALS AND METHODS

2.1 Experimental Setup

The experimental setup consists of a system of five simple pendulums suspended on thin strings. Each pendulum is formed by a metal nut attached to the end of the string. To enable reliable detection in the video, the nuts were coated with a distinctive purple color. The purple color was selected due to its high contrast with the background and its relatively low occurrence in the surrounding environment. This choice simplifies segmentation and reduces the likelihood of false detections caused by similarly colored objects. The motion of the pendulums was recorded using a stationary digital camera with a frame rate of 30 frames per second. The recorded video had a resolution of 1920 × 1080 pixels, ensuring sufficient spatial detail for reliable object detection and trajectory extraction. The camera was positioned below the pendulums and oriented vertically upward, capturing their motion against the ceiling background. This configuration minimizes mutual occlusion between the pendulums and ensures a stable field of view. Due to non-uniform illumination conditions, one of the pendulums exhibited reduced visibility in the recorded video. This resulted in less reliable color detection and represented a typical scenario of imperfect lighting conditions in practical applications.



Figure 1. Experimental setup

2.2 Video Processing Pipeline

The recorded video was processed using a custom program written in Python with the OpenCV library [Bradski 2008, Kaehler 2017, OpenCV 2024, Python 2024]. Each frame of the video was converted from the RGB color space to the HSV (Hue, Saturation, Value) color space, which is more suitable for color-based segmentation [Gonzalez 2018].

Object detection was performed by applying a color threshold to isolate pixels corresponding to the purple color of the pendulum masses [Klette 2014]. Two different threshold configurations were used:

- A baseline configuration with narrower HSV limits,
- an improved configuration with extended HSV ranges and additional filtering constraints.

Following thresholding, morphological operations including median filtering, dilation, and erosion were applied to reduce noise and improve mask quality.



Figure 2. Color mask – baseline method



Figure 3. Color mask – improved method

The HSV color space was selected due to its robustness in color-based segmentation tasks. Unlike the RGB color model, HSV separates chromatic information (hue) from intensity (value), which makes it more suitable for object detection under varying lighting conditions [Gonzalez 2018]. However, despite this advantage, HSV-based segmentation remains sensitive to significant illumination changes, particularly in the saturation and value components. This limitation becomes critical in scenarios where objects are unevenly illuminated or partially shadowed.

2.3 Object Localization

After segmentation, contours corresponding to detected objects were extracted from the binary mask. For each detected region, the centroid was calculated using image moments, representing the estimated position of the pendulum in the image [Szeliski 2010].

To ensure consistent identification of individual pendulums across frames, detected objects were sorted according to their horizontal position. This approach allows stable labeling of pendulums as N1 to N5.

However, under imperfect lighting conditions, the detected region may be incomplete or distorted, leading to inaccuracies in centroid estimation. This effect is particularly visible for objects with lower contrast in the image.

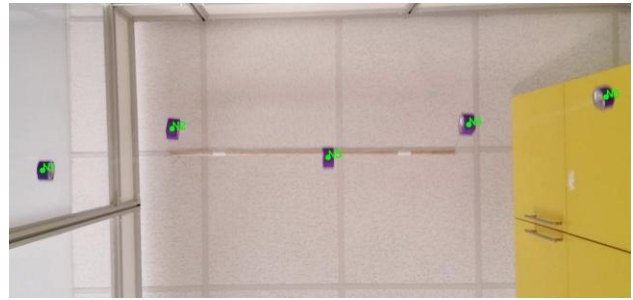


Figure 4. Detected centroids – baseline method

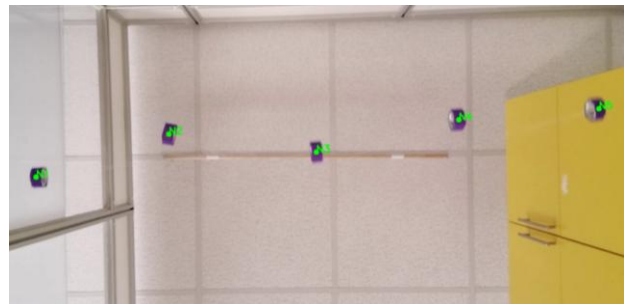


Figure 5. Detected centroids – improved method

Although centroid-based localization provides a simple and computationally efficient method for position estimation, its accuracy strongly depends on the completeness of the detected object region and the geometric consistency of the observed shape [Hartley 2004]. In cases where the segmented region is partially missing or distorted due to poor lighting conditions, the calculated centroid may be significantly shifted from the true object center. This effect represents one of the main sources of error in the presented tracking approach.

2.4 Data Acquisition

For each video frame, the vertical coordinate of each detected pendulum was recorded. The vertical axis was selected because it corresponds to the dominant direction of oscillatory motion in the experimental setup.

The recorded data were exported into a CSV file containing the frame index, time, and vertical position of each pendulum. The time corresponding to each frame was calculated based on the known frame rate of the video.

2.5 Evaluation Method

To evaluate the stability and robustness of the tracking process, temporal derivatives of the detected trajectories were analyzed. Specifically, the first-order and second-order differences of the vertical position were computed.

The second-order derivative was used as the primary evaluation metric, as it amplifies high-frequency variations in the signal. These variations are typically caused by instability in object detection rather than by the physical motion of the pendulum.

By comparing the second-order derivatives obtained using the baseline and improved masking approaches, it is possible to quantify the level of noise in the detected trajectories and assess the effectiveness of the proposed improvements.

2.6 Limitations of the Approach

Despite its simplicity and effectiveness, the proposed method has several limitations. The tracking approach relies on color-based segmentation, which makes it inherently sensitive to changes in illumination and color representation.

The selection of HSV thresholds requires manual tuning and may not generalize well across different environments or camera settings. In addition, the method assumes that the tracked objects are visually distinguishable from the background, which may not always be the case.

Another limitation is related to the use of centroid-based localization. As discussed previously, this method is sensitive to incomplete or distorted object regions, which may occur under challenging imaging conditions.

These limitations suggest that further improvements could be achieved by incorporating adaptive thresholding techniques or more advanced object detection methods.

3 RESULTS AND DISCUSSION

3.1 Noise Analysis of Detected Trajectories

The quality of object tracking was evaluated by analyzing the temporal behavior of the detected trajectories. Since direct comparison of positional data is influenced by differences in initial conditions and motion characteristics of individual pendulums, the evaluation was based on the second-order temporal derivative of the vertical position.

The second-order derivative emphasizes rapid changes in the signal, which are primarily caused by instability in object detection rather than by the physical motion of the system. Therefore, it provides a suitable metric for assessing the robustness of the tracking algorithm.

Figures 6 and 7 show the comparison of the second-order derivative for two selected pendulums (N1 and N5) under different masking conditions.

3.2 Comparison of Baseline and Improved Detection

In the baseline configuration, significant differences can be observed between the signals corresponding to pendulums N1 and N5 (Fig. 6). While the signal of N1 remains relatively smooth, the signal of N5 exhibits pronounced fluctuations and high-amplitude spikes. These artifacts are caused by incomplete or unstable detection of the object due to insufficient color segmentation under imperfect lighting conditions.

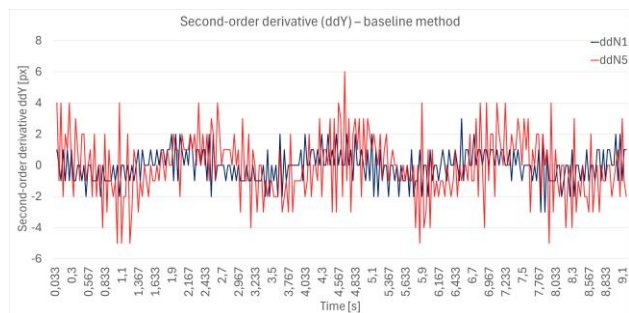


Figure 6. Second-order derivative (ddY) – baseline method

In contrast, the improved masking approach results in a substantial reduction of these fluctuations (Fig. 7). The signals corresponding to N1 and N5 become more consistent, and the amplitude of high-frequency variations is visibly reduced. This indicates that the improved method provides more stable object localization across consecutive frames.

It can also be observed that the noise present in the baseline method is not uniformly distributed over time. Instead, it appears as intermittent spikes, which correspond to moments of partial detection failure. These irregularities are significantly reduced in the improved method, where the signal exhibits more consistent behavior.

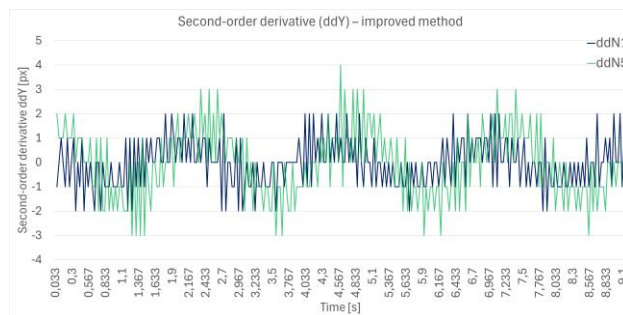


Figure 7. Second-order derivative (ddY) – improved method

3.3 Quantitative Evaluation

To further quantify the improvement, statistical measures of the second-order derivative were evaluated. Specifically, the standard deviation of the ddY signal was calculated for each pendulum. The results indicate that the improved masking approach reduces the variability of the detected trajectories. In particular, the standard deviation of the second-order derivative for the poorly visible pendulum (N5) was noticeably lower compared to the baseline method. This confirms that the proposed modification effectively suppresses noise caused by unstable detection and improves the overall robustness of the tracking system.

3.4 Sensitivity to Lighting Conditions

In order to further evaluate the robustness of the proposed approach, the sensitivity of the tracking algorithm to illumination conditions was analyzed. The baseline method showed a strong dependence on lighting quality, where even minor variations in illumination resulted in incomplete segmentation of the observed objects.

This effect was particularly evident for pendulum N5, which was partially affected by shadowing. The resulting segmentation inconsistencies led to unstable centroid estimation and increased noise in the extracted trajectory.

In contrast, the improved masking approach demonstrated higher tolerance to such variations. By extending the HSV threshold range and refining the filtering process, the method was able to maintain more consistent object detection even under suboptimal lighting conditions.

These findings confirm that proper adjustment of segmentation parameters plays a critical role in ensuring reliable tracking performance in real-world scenarios.

4 DISCUSSION

The presented results clearly demonstrate that the accuracy of color-based object tracking is strongly influenced by illumination conditions. In the baseline configuration, insufficient color segmentation leads to incomplete or fragmented object regions. As a consequence, the calculated centroid does not correspond to the true geometric center of the object, resulting in positional errors, which is a known limitation of image-based measurement systems under imperfect detection conditions [Trucco 1998].

This effect is particularly pronounced for objects with reduced visibility, as observed in the case of pendulum N5. Due to lower contrast between the object and the background, the segmentation process produces unstable regions, which directly translates into high-frequency fluctuations in the extracted trajectory.

The use of the second-order temporal derivative proved to be an effective tool for revealing these inaccuracies. While the original position signals may appear relatively smooth, the second-order derivative amplifies rapid variations caused by

detection errors. This makes it a suitable metric for evaluating the robustness of tracking algorithms independently of the underlying physical motion.

The improved masking approach significantly reduces these issues by extending the HSV threshold range and refining the segmentation process. As a result, the detected object regions are complete and more stable, leading to more accurate centroid estimation and reduced noise in the trajectory data.

Despite these improvements, the method still has certain limitations. The performance remains dependent on appropriate selection of HSV thresholds, which may require manual tuning for different experimental conditions. Additionally, extreme lighting variations or reflections may still lead to partial detection failures.

Nevertheless, the proposed approach provides a simple and effective solution for improving tracking robustness without requiring complex models or computationally expensive algorithms. This makes it particularly suitable for educational applications and low-cost experimental setups.

5 CONCLUSION

This paper presented an approach for tracking multiple pendulums using video analysis under imperfect lighting conditions. The method is based on color segmentation in the HSV color space combined with centroid-based object localization.

The results showed that standard color thresholding may lead to unstable object detection when illumination conditions are not optimal. This instability directly affects the accuracy of the extracted trajectories, especially for objects with reduced visibility.

To address this issue, an improved masking approach was introduced, enhancing the robustness of the segmentation process. The effectiveness of the method was evaluated using the second-order temporal derivative of the detected trajectories, which proved to be a suitable metric for identifying noise caused by detection errors.

The comparison of baseline and improved approaches demonstrated a clear reduction in high-frequency noise, particularly for the most affected pendulum. These results indicate that even relatively simple modifications in the preprocessing stage can significantly improve tracking stability. The proposed solution is computationally efficient and easy to implement, making it suitable for applications such as educational experiments and low-cost measurement systems. Future work may focus on adaptive thresholding or advanced object detection methods to further improve robustness under challenging conditions.

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REFERENCES

- [Bradski 2008] Bradski, G. and Kaehler, A. Learning OpenCV: Computer Vision with the OpenCV Library. Sebastopol: O'Reilly Media, 2008. ISBN 978-0596516130
- [Gonzalez 2018] Gonzalez, R.C. and Woods, R.E. Digital Image Processing, 4th ed. Harlow: Pearson, 2018. ISBN 978-0133356724
- [Hartley 2004] Hartley, R. and Zisserman, A. Multiple View Geometry in Computer Vision, 2nd ed. Cambridge: Cambridge University Press, 2004. ISBN 978-0521540513
- [Kaehler 2017] Kaehler, A. and Bradski, G. Learning OpenCV 3: Computer Vision in C++ with the OpenCV Library. Sebastopol: O'Reilly Media, 2017. ISBN 978-1491937990
- [Klette 2014] Klette, R. Concise Computer Vision: An Introduction into Theory and Algorithms. London: Springer, 2014. ISBN 978-1447163206
- [Kondrat 2025] Kondrat, M., et al. Real-Time Monitoring of 3D Printing Process by Endoscopic Vision System Integrated in Printer Head. Applied Sciences, 2025, Vol. 15, No. 17, 9286. <https://doi.org/10.3390/app15179286>
- [Nowakowski 2025] Nowakowski, M., Kurylo, J. and Dabrowski, P. Object Tracking-Based "Follow-Me" for Optionally Unmanned Ground Vehicles. Defence Science Journal, 2025, Vol. 75, No. 2, pp. 199-205. ISSN 0011-748X
- [OpenCV 2024] OpenCV.org. OpenCV Documentation [online]. [2026-03-30]. Available from: <https://docs.opencv.org>
- [Python 2024] Python Software Foundation. Python Documentation [online]. [2026-03-30]. Available from: <https://docs.python.org>
- [Szeliski 2010] Szeliski, R. Computer Vision: Algorithms and Applications. London: Springer, 2010. ISBN 978-1848829343
- [Trucco 1998] Trucco, E. and Verri, A. Introductory Techniques for 3-D Computer Vision. Upper Saddle River: Prentice Hall, 1998. ISBN 978-0132611084
- [Zidek 2024] Zidek, K., Duhancik, M., Hrehova, S. Real-Time Material Flow Monitoring in SMART Automated Lines using a 3D Digital Shadow with the Industry 4.0 Concept. In: 2024 25th International Carpathian Control Conference (ICCC), Krynica Zdroj, Poland, 2024, pp. 1-6. DOI: 10.1109/ICCC62069.2024.10569500