Computer Vision Framework for Multi-body System of Domino Chain Effect

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Abstract Domino chain effect is a complex, marginally stabilized multi-body dynamics system. Despite various proposed models, results remain inconclusive. This paper presents a new methodology with high-speed camera and computer vision for precise data capture. Key steps include optimized recording conditions, video preprocessing, edge detection, and reconstruction. Findings reveal velocity increases post initial push and consistent fluctuations after collisions. Further discussion extends this approach to a longer domino chains for a more thorough analysis of the domino chain effect.

1. Introduction

The domino chain effect serves as a paradigm of marginally stabilized systems, where a sufficient destabilization force applied to a single element in the chain initiates the successively topple of the entire system. This phenomenon addresses broad interests for its beauty of marginal stabilization, it has become a game for children and a mass challenge for architecture with marginally stable elements. The phrase domino chain effect is often referenced to illustrate the perturbations in interconnected systems.

Research on the multi-body dynamics of domino chains under gravitational fields spans diverse theoretical and computational approaches. Early in 1983, McLachlan *et.al* [1] proposed a 2D model, simplifying each domino block by neglecting the width. As the chain's propagation is determined by the collision, other models simplify the system, including representing each domino block as a massless rod [2], considering single elastic collisions between neighboring dominoes [3][2], inelastic single collisions with subsequent contact with sliding with friction between both the base surface and dominoes [4][5].

While all theoretical models have been proposed, tested, and debated over several decades, there's no agreement upon a definitive model that captures the behavior of individual blocks and the overall chain. However, there is general agreement among researchers that improved data resolution would yield a more comprehensive understanding of domino chain behavior. Common experiment methods include using a stopwatch, photo-gates, and high-speed video. Stronge and Shu [6], for instance, has built up a slow-motion video setup capturing and analyzing the domino chain effect system with a frame speed of 600-1200 fps, although the subsequent analytical approach remains insufficiently documented.

This study aims to refine and evaluate the methodology of utilizing high-speed video with computer vision analysis to understand the domino chain effect. We propose an accessible and precise experimental setup to facilitate detailed quantitative analyses, offering a new methodological framework for investigating the domino chain effect.

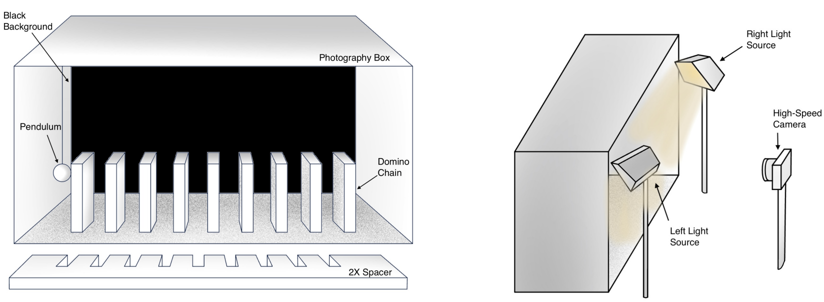
2. Experimental Techniques

This section provides an overview of the setup for recording and processing workflow, emphasizing features critical to the methodology's quality.

2.1 Experiment Setup

The dominoes are placed in linear chain with uniform or non-uniform spacing on a flat plane. The surface of the plane and the back face of each domino block are lined with sandpaper to minimize sliding upon collision. Spacers are employed to position the domino blocks at consistent intervals for spacing configurations. A pendulum is used to standardize the initial push, ensuring repeatability in the force applied to initiate the chain reaction.

To establish the recording setup, a photography box is used with black paper as the background to enhance contrast and two light sources are positioned on either side to minimize shadow effects. A high-speed camera, capturing at 480–1000 fps, is mounted on a fixed frame 1.5 meters from the experiment to reduce edge distortion. A schematic of the experimental setup is provided in Figure 1. The setup is tested under varying parameters of domino chains shown in Figure 3, with each configuration repeated five times for recording.



a). The front-view sketch of the setup illustrates the interior of the photography box, featuring a black background, a sandpaper base surface, a domino block with sandpaper, and a pendulum.

b). The side-view sketch of the setup shows the relative positions of the photography box, the light source, and the high-speed camera.

FIGURE 1. *Experimental set-up sketch*

2.2 Data Extraction and Processing

The data extraction code composed of video preprocessing, initial and instantaneous position detection, reconstructing and derive angular position with de-noise to get its corresponding velocity.

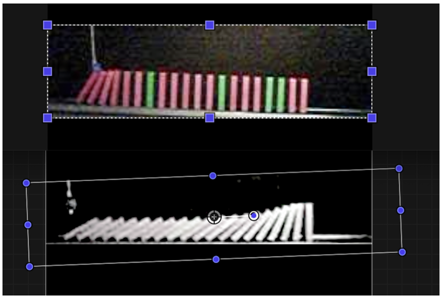
2.2.1 Video Preprocessing

The high-speed camera balances resolution and frame rate, operating at 1000 fps with relatively low resolution, as shown in Figure 2a). To ensure accurate detection, contrast between the domino blocks and the background must be enhanced before applying the algorithm. Precise reconstruction of each block's angular positions requires manually aligning the camera frame to maintain a horizontal baseline. Minor edge distortion corrections can further improve detection accuracy.

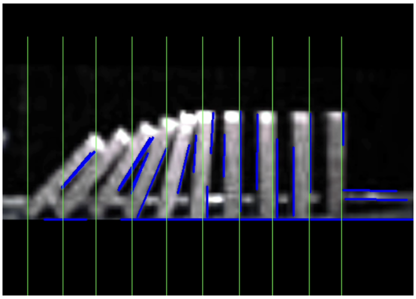
2.2.2 Initial and instantaneous position detection

To simplify multi-body dynamics detection while minimizing computational demands, simple edge detection and basic statistical methods are employed.

To determine the baseline and initial positions of the domino blocks in general, edge positions are detected in both the x and y directions over a sequence of 50–100 frames, using python OpenCV library [7]. Based on statistical distribution of initial edge positions, the most frequent value can be taken as the exact position with standard deviation as the uncertainty. Only the right edge of each block is analyzed along the x-axis, specifically, the $2 \cdot N$ most frequent x-values (corresponding to N domino blocks in the frame) are identified, with half of the value (the odd-numbered values) representing the initial positions of the right edges, refer to Figure 2b).



a). Processed frame (bottom) compared with the original frame (top), showcasing enhanced clarity and reduced noise to facilitate improved contour recognition.



b). The frame shows the edge detection process, with the slanted blue line (instantaneous detected edge) and the green lines (baseline and initial block positions).

FIGURE 2. *Video Processing and Computer Vision Edge Detection*

Assuming the right bottom corner of each domino block stays fixed during collision, only edges intersecting the baseline near each block's initial position are considered valid. By detecting edges frame-by-frame throughout the toppling sequence and converting them into intersection angles with the baseline, the complete set of instantaneous angular positions for each block can be recorded.

2.2.3 Reconstructing and Derive Angular Position and Velocity

By converting the instantaneous angular position for each domino block, the position on each domino block can be reconstructed. Shown by Figure 3, the trajectory of each domino block's top right corner are reconstructed as scatter plot on the final frame.

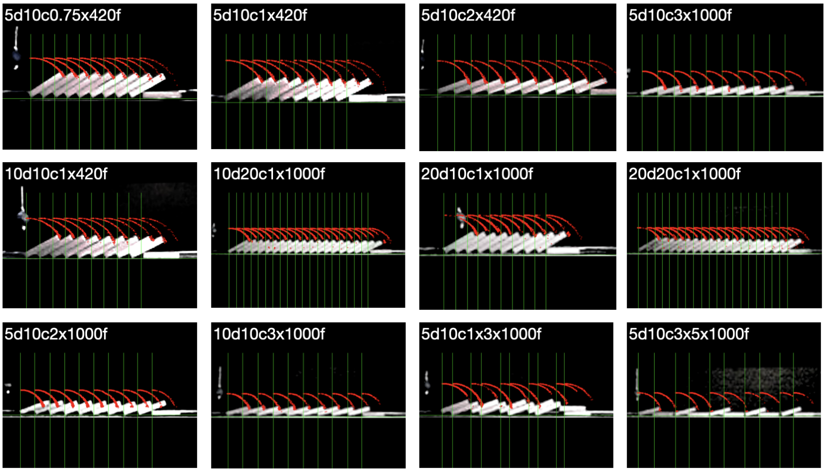


FIGURE 3. *Reconstructed position trajectory graph of each domino block for different setting of the domino model.*[1] *The first row test changing of spacing, the second and third row examines different initial push with longer chains, with non-even spacing.*

By aligning the data from five repetitions and compiling all scatter points for each domino block in the chain, a LOESS [8] filter with a window size of 30 is applied to generate a continuous angular position curve refer to Figure 4 Taking the derivative of this position curve provides the angular velocity. A second application of the LOESS filter, with a window size of 20, produces a final continuous instantaneous velocity profile, illustrated on 5.

[1] An example of the code for different setting $(5d|10c|1x|420f)$, which $(5d)$ represents pendulum initial angle, $(10c)$ represent of domino blocks in the chain, $(1x)$ means spacing = block width. (similarly, $(2x)$ means spacing = 2× block width), $(420f)$ means using a 420[fps] high speed recording.

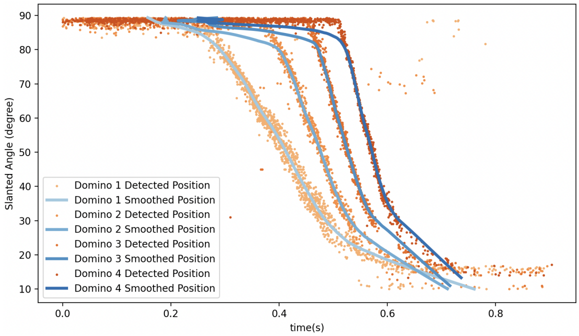


FIGURE 4. *The plot shows aligned position data points with LOESS-smoothed curves, for the first 4 domino blocks in a* $3x$ *spacing chain with* $5d$ *of initial pendulum push.* [1]

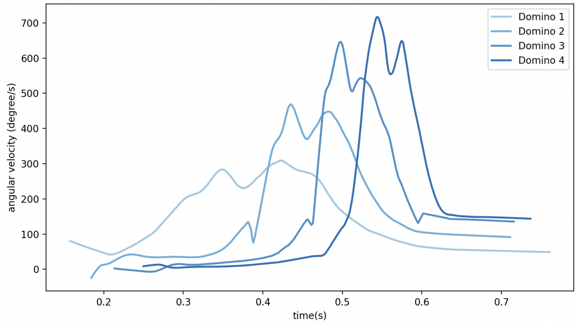


FIGURE 5. *The plot shows the angular velocity curve corresponding to Figure 4, highlighting a clear pattern of increasing speed after the initial push.*

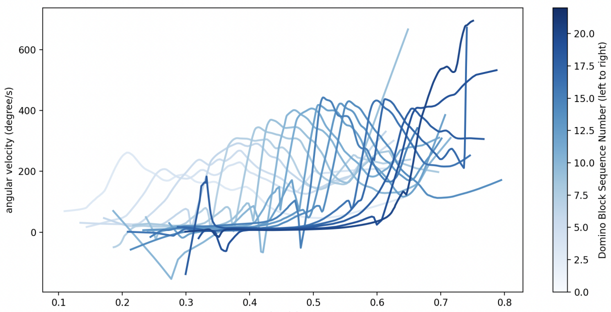


FIGURE 6. *The plot shows the angular velocity curve for set* $10d20c1x1000f$*, revealing a clear convergence of speed after the initial domino blocks.*[1]

3. Discussion and Future Works

The methodology outlined above enables the acquisition of comprehensive and precise angular velocity and position data for each domino block, and enables further numerical and quantitative analysis. As illustrated in Figure 6, a progressive increase in velocity is observed across successive dominoes following the initial push by the pendulum, and the velocity start to converge after the initial domino blocks. Additionally, the velocity fluctuations after each collision exhibit a consistent pattern across the blocks, but with greater noise in the later domino blocks. The high-speed video reveals multiple collisions between dominoes, presenting a significant challenge for most theoretical models, which often assume single-collision events.

The current methodology is limited to analyzing short chains (fewer than 20 domino blocks) due to the fixed camera setup. Introducing a movable or multi-camera system could facilitate the study of longer chains, enabling a more comprehensive analysis of domino dynamics.

Further analysis can be conducted to validate theoretical models of the domino chain effect with precise quantitative methods. While current analysis focuses on angular position and velocity of individual blocks without capturing velocity along the toppling direction, it surpasses traditional studies of asymptotic chain velocity. This approach enables exploration into how energy propagates through mechanical transmission across successive dominoes, also how the geometry of the blocks influences energy transfer. This analysis provides foundation for modeling the propagation behavior from a wave mechanics perspective, providing insights into the similarities between domino chain reactions and wave-like energy transmission patterns. Such a comprehensive approach enhances our understanding of the dynamics underlying the domino chain effect and its potential applications in mechanical and wave-based systems.

4. Conclusions

This paper develops a high-speed video with computer vision methodology approach to analyze the domino chain effect, considering approachability and effectiveness as the top design objectives. The methodology provides precise data on the angular position and velocity of each domino block. Compared with past experimental methods of focusing on examining the asymptotic behavior through the domino chain, this methodology would provide a more comprehensive approach to evaluating domino dynamics. Future research could explore various configurations and surface properties, further advancing applications in systems involving mechanical and wave-like energy transmission.

Code Availability

Code can be found in Github Repository.

References

[1] B. G. McLachlan, G. Beaupre, A. B. Cox, and L. Gore, Falling dominoes(d. e. daykin), *SIAM Review*, vol. 25, no. 3, pp. 403–404, 1983. DOI: 10.1137/1025085. eprint: https://doi.org/10.1137/1025085. Available at <https://doi.org/10.1137/1025085>.

[2] C. W. Bert, Falling dominoes, *SIAM review*, vol. 28, no. 2, pp. 219–224, 1986.

[3] *Towing Icebergs, Falling Dominoes, and Other Adventures in Applied Mathematics*. 1998.

[4] J. M. J. van Leeuwen, The domino effect., *American Journal of Physics*, vol. 78, no. 7, pp. 721–727, 2010.

[5] D. E. Shaw., Mechanics of a chain of dominoes., *American Journal of Physics*, vol. 46, no. 6, pp. 640–642, 2010.

[6] S. W. J. and S. D., Falling dominoes(d. e. daykin), *Proc. R. Soc. Lond.*, vol. A418, pp. 155–163, 1988. DOI: 10.1137/1025085. Available at <http://doi.org/10.1098/rspa.1988.0077>.

[7] G. Bradski, The OpenCV Library, *Dr. Dobb's Journal of Software Tools*, 2000.

[8] P. C. Austin and E. W. Steyerberg, Graphical assessment of internal and external calibration of logistic regression models by using loess smoothers, *Statistics in Medicine*, vol. 33, no. 3, pp. 517–535, 2013. DOI: 10.1002/sim.5941.