Computer Vision Framework of Multibody Domino Chain System

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01 Introduction & Motivation

The domino chain effect serves as a a prototypical marginally stable system, where a sufficient force applied to a single element in the chain initiates the the successive toppling of the dominoes.

Simplified models, like massless rods[1], single elastic/inelastic collisions[2][3], and relative sliding[4] have been proposed and discussed, however, experimental validation remains limited. This study refines the use of high-speed video and computer vision techniques to analyze the domino effect.

Evolution of Approach

Initial 2D analysis revealed multi-collision effects and enabled examination of the domino wave's acceleration stage before reaching a plateau of propagation speed. However, this method failed to capture out-of-plane block rotations (Fig. 1.1), which exhibit a periodic influence on propagation speed, highlighting an overlooked aspect of the chain's dynamics.

A 3D reconstruction system was developed, enabling the full six degrees of freedom for each domino block within the chain reaction to be captured and analyzed.

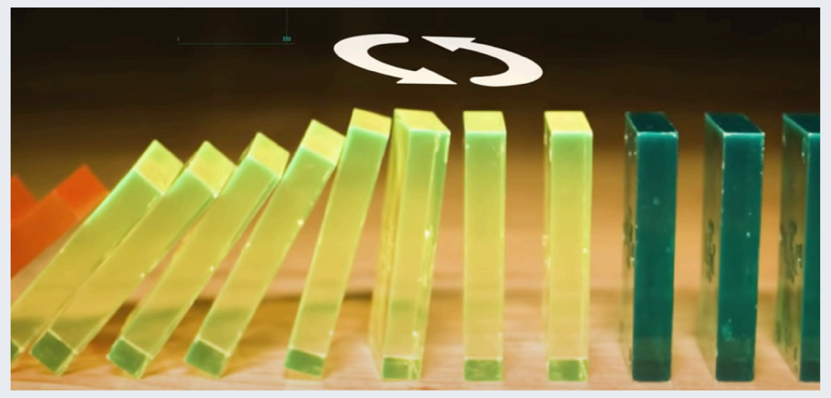

Fig. 1.1 Relative rotation perpendicular to the toppling direction occurs during domino collisions, as captured by a high-speed camera[5]. This back-and-forth twisting motion appears to be periodically influence the toppling speed.

02 2D Motion Captures

Methodology Pipeline

Using the calculated initial positions from edge detection, we reconstruct the domino toppling motion in 2D. Several setups are shown in Fig. 2.2, and the corresponding angular velocities extracted from the chain are presented in Fig. 2.3.

Video pre-processing → Initial position estimation → Instantaneous edge detection → Re-calculate instantaneous angular position → Synchronize repetitions and denoising → Angular velocity computation

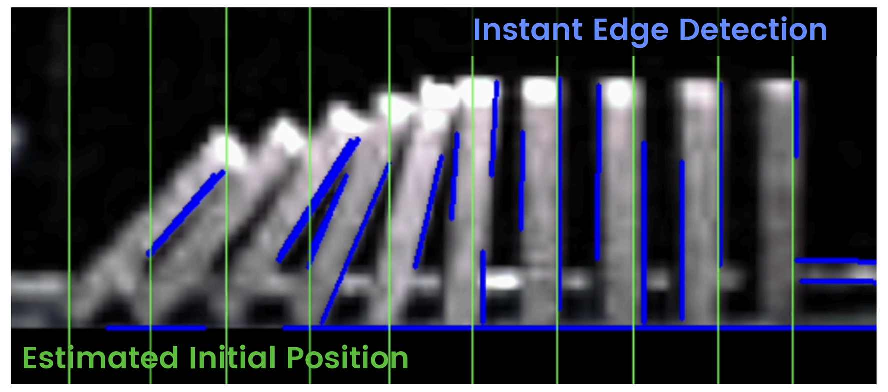

Fig. 2.1 2D motion capture by determining initial position and detecting instantaneous edges.

Assumptions & Limitations

- No relative sliding (each block's lower-right edge is fixed)
- Off-plane rotations ignored
- Near-edge camera distortion ignored
- Only ~20 blocks can be captured

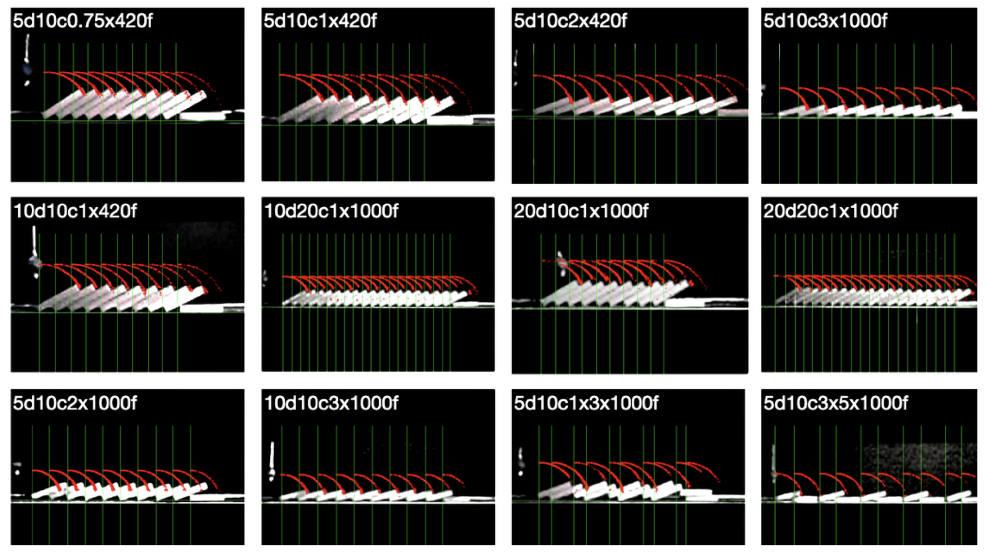

Fig. 2.2 Reconstructed trajectories of domino blocks using edge detection for different setups.

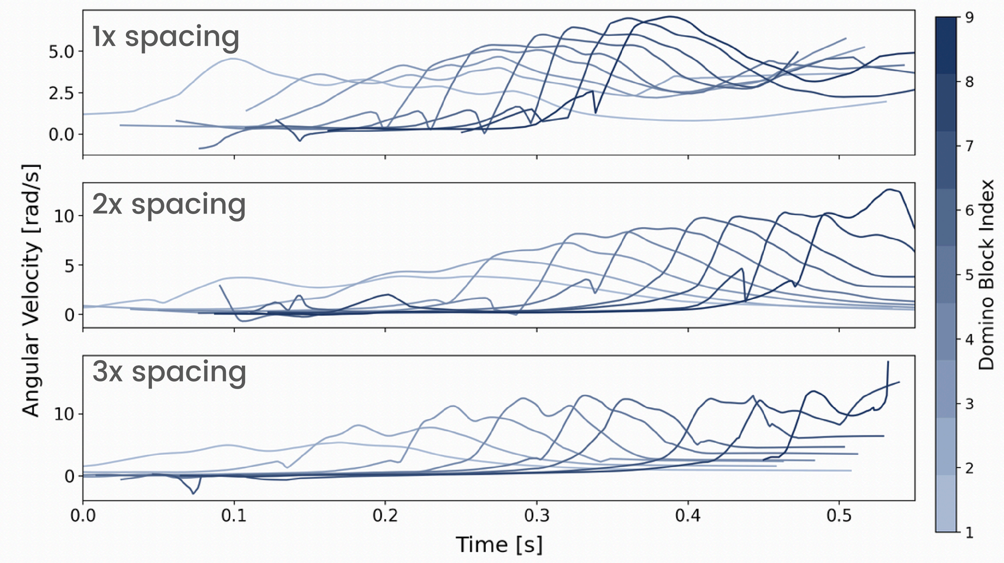

Fig. 2.3 Angular velocity curves during the toppling of domino blocks, illustrating initial increase in angular velocity for various spacings.

03 3D Reconstruction

Methodology Pipeline

1. Record & synchronize videos (Fig. 3.1)
2. Camera parameter calibration (Fig. 3.2)
3. Color marker tracking (Fig 3.3)
4. Motion reconstruction (triangulation)
5. Reorient to world reference frame (Fig. 3.5)

3. Color marker tracking → reconstruction → 4. Motion reconstruction (triangulation); 4. → reproject for uncertainty check (Fig. 3.4) → 3.

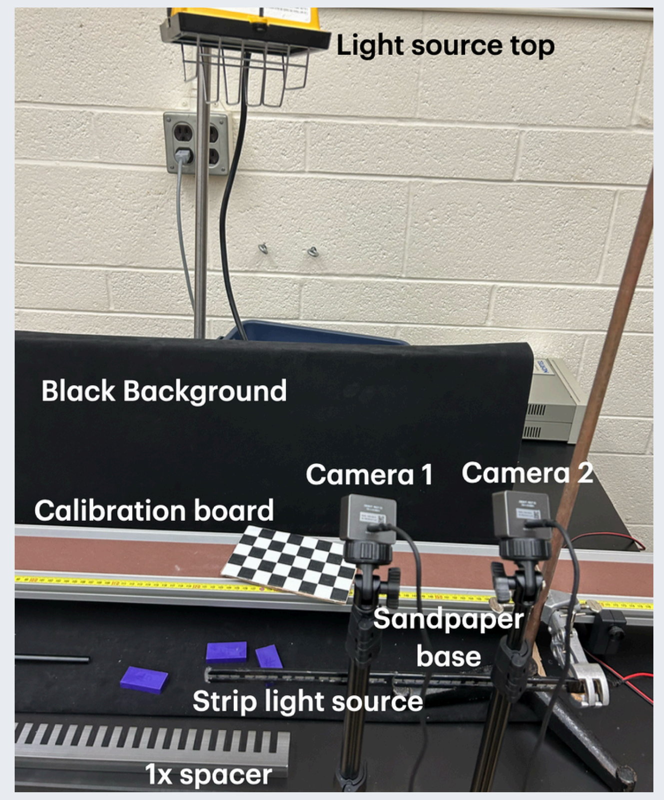

Fig. 3.1 3D reconstruction apparatus setup.

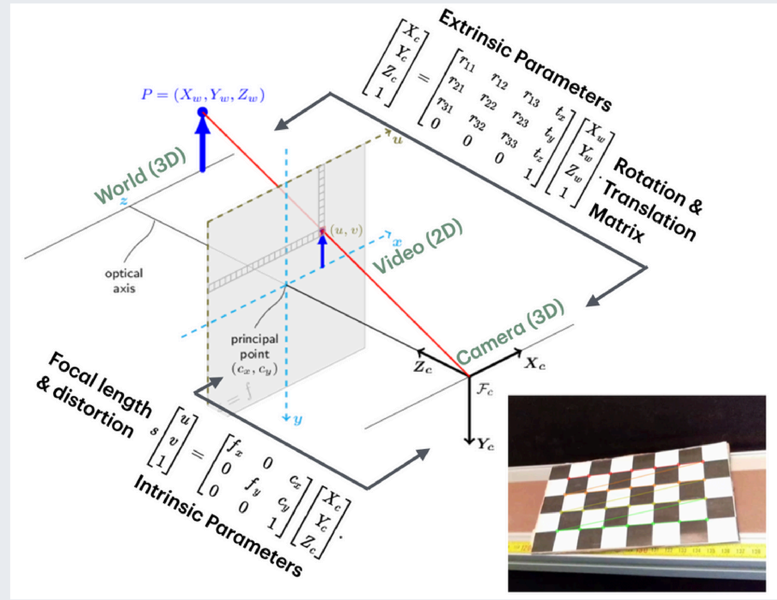

Fig. 3.2 Pinhole camera calibration model[6][7] using a checkerboard pattern to estimate intrinsic parameters and distortion coefficients.

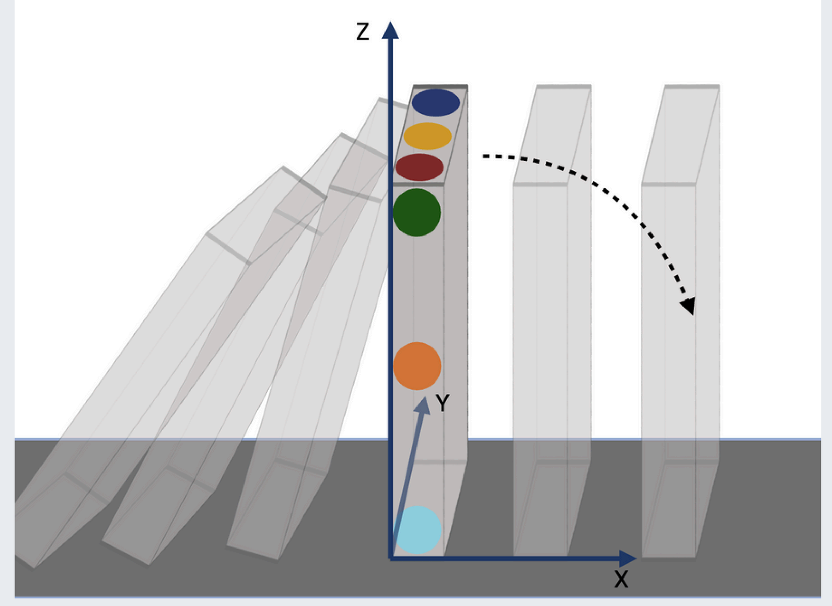

Fig. 3.3 Color marker labels with reference frame orientation used in the model.

Challenges

The reconstruction error in Fig. 3.4 averages around ±3[mm]. However, systematic errors in color marker tracking remain difficult to verify. To address this, we are setting up a global reference anchor system (similar to those used in 3D printing).

While the designed pipeline theoretically captures full degrees of freedom, it still shows depth estimation uncertainty. As seen in Fig. 3.5, marker trajectories are consistently over-slanted, suggesting a depth bias. This likely results from the use of only six co-planar markers, as well as imprecise calibration and world anchor frame setup. To address this, we plan to introduce front-facing markers to improve depth referencing and establish a more robust reference frame system.

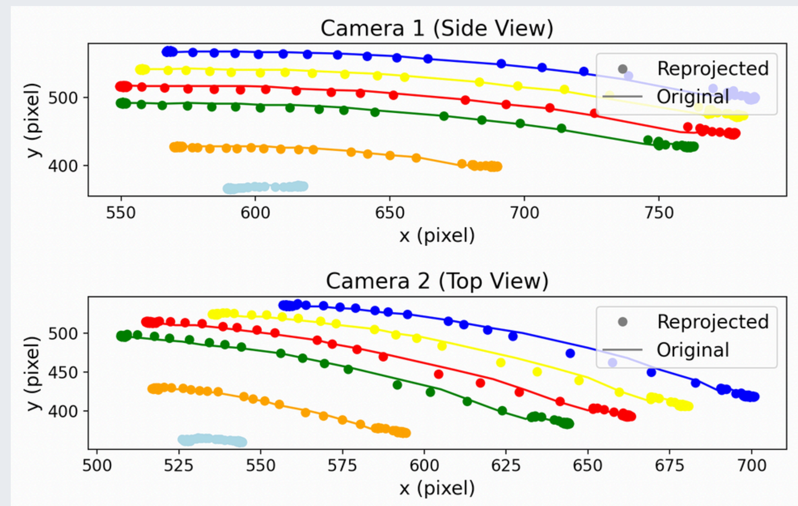

Fig. 3.4 Methodology error assessment by reprojecting the 3D model into the original camera view and comparing it with tracked positions across frames.

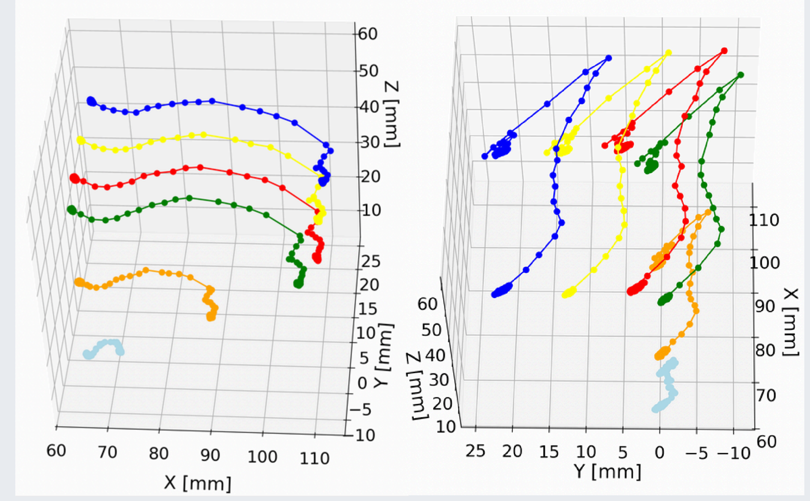

Fig. 3.5 Reconstructed 3D positions of color markers on a single domino block, shown from side and front views.

04 Results & Findings

Assuming rigid body motion, we project the absolute positions of the color markers (Fig. 4.1) to compute translational and rotational velocities, as shown in Fig. 4.2. Rotation ω_y and sliding v_x along the toppling direction dominate the motion, but wobbling and sliding in other directions remain non-negligible. The observed wobble arises from asymmetric collision points between adjacent domino blocks.

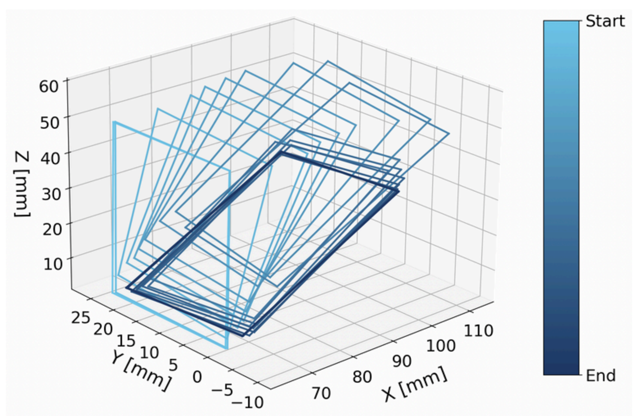

Fig. 4.1 Reconstructed instantaneous 3D toppling motion of domino blocks.

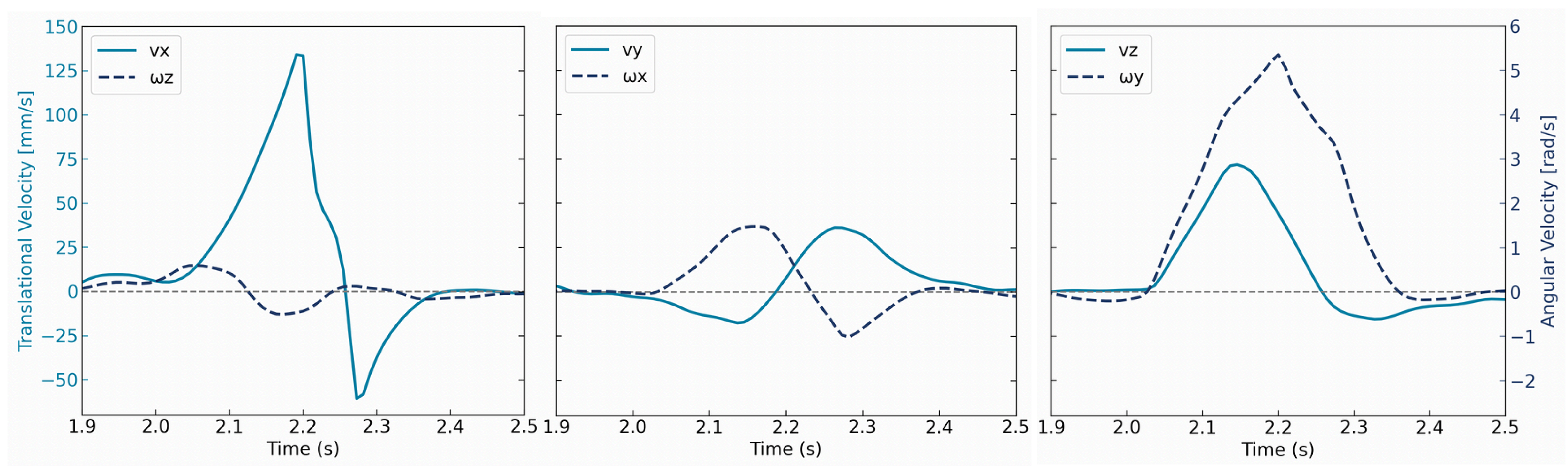

Fig. 4.2 Rotational and translational velocities are shown in pairs. The wobble in ω_z, reverse alignment of v_y and ω_x, and COM lift in v_z indicate that rotations perpendicular to the toppling direction are non-negligible.

05 What's Next!

Theoretical Models

- Validate the reconstruction with asymptotic models
- Explore analogies with nonlinear (solitary) waves

Material & Mechanical Effect

- Compare elastic (rubber) vs. inelastic (metal) dominoes
- Effect of varying internal mass distribution in domino blocks
- Investigate effects of curved vs. straight trajectories
- Measure the sliding between blocks and ground to assess the friction with energy dissipation and momentum transfer.

Methodology Verification

- Repeat single-block fall tests to quantify uncertainty
- When does a three-camera system become necessary for full 3D tracking?

Off-plane Rotation

- How does off-plane rotation (i.e. around the z axis in Figure 3.3) affect system stability?
- Is the rotation purely a result of non-ideal experimental conditions?
- Under what conditions does the rotation would stop propagation?
- Can we fully predict future motion?

and even more...

- Implement a moving camera system to track longer chains.
- How does the domino chain effect relate to the theory of seismic waves?

References

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