Video analysis of juggling ball trajectories

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1 Abstract

This report presents a proof of concept for extracting position and velocity data from video of moving objects. Using a custom object tracking algorithm written in Python, the positions and velocities of three juggling balls were extracted from 618 frames of high-speed video. The results are plotted and shown to be consistent with the expected physical behavior. Finally, the behavior of the system's center of mass over time is characterized and shown to have an average deviation of 3 cm from the time-averaged center of mass.

2 Introduction

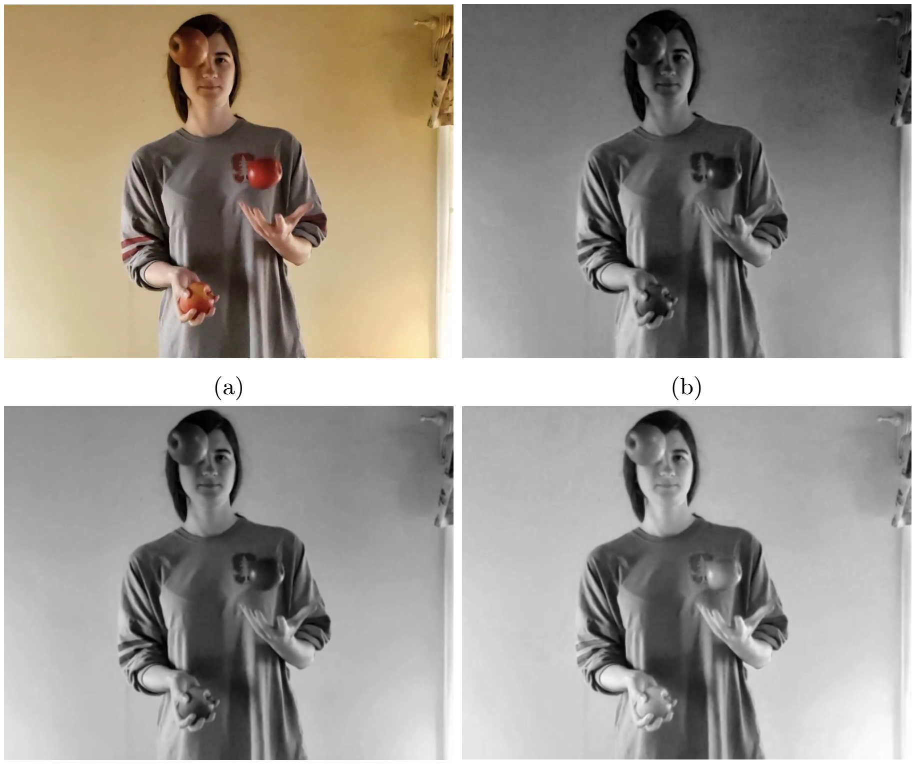
With camera resolutions on the order of 10 million pixels, modern smartphones offer a powerful and convenient way to collect detailed position information from physical systems. In addition, many smartphones have high-speed capabilities ranging from 240 to 960 frames per second or beyond, providing an easy way to study small-scale time regimes that would otherwise require expensive video equipment.

This report analyzes a video of three apples being juggled, filmed using a standard smartphone at 240 frames per second, to extract detailed position and velocity information on the trajectories of the apples. The Analysis section below discusses the details of the image processing and object tracking algorithm. The Results section presents plots of the collected position and velocity data, interprets the results in terms of the system's physical behavior, and briefly analyzes the behavior of the system's center of mass.

3 Analysis

Figure 1 shows a representative frame from the source video along with its constituent color channels.

By visual inspection, the apples appear to be much darker in the green channel (1c) than in the red channel (1d), while the rest of the frame remains at roughly the same intensity. To isolate the apples, the green channel is subtracted



(a) (b) (c) (d)

Figure 1: A representative frame from the source video, showing a) full color, b) blue channel, c) green channel, and d) red channel.

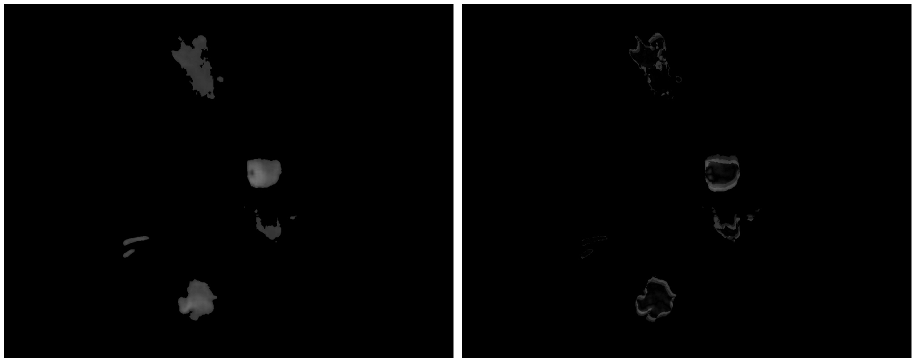
from the red channel, and a minimum threshold of 50 is applied to the resulting difference; in addition, pixels above 220 are removed, as these represent the majority of random noise in the frame:

$$\begin{cases} r-g & 50 < r-g < 220 \\ 0 & otherwise \end{cases} \tag{1}$$

The outcome of this process is shown in Figure 2a.

The color difference threshold is effective at removing most of the background, but because portions of the juggler's skin is similar in color to the apples, there is some interference from the hands and face. This is particularly visible at the top of Figure 2a, where one of the apples has overlapped and merged with the signal from the face.

To reduce this interference, a difference is taken between each pair of consecutive frames, resulting in the image shown in Figure 2b. This process takes advantage of the motion of the apples to isolate them from static background



(a) (b)

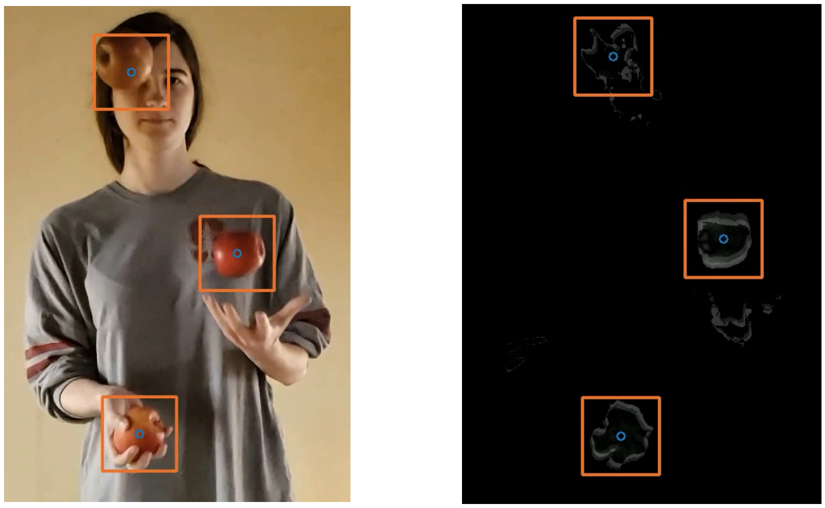
Figure 2: Frame from Figure 1 after processing, showing a) result of applying the color distance threshold, and b) change in pixel value compared to the subsequent frame of the video. In the latter image, the signal from the juggler's face is largely removed, allowing the tracking algorithm to remain locked onto the apple.

sources. There is still some interference from the hands, but the signal from the face is almost entirely absent.

To track the apples throughout the video, the estimated positions of the three apples are entered manually for the first two frames, providing the tracking algorithm with initial position and velocity information. To track a given apple into the following frame, the algorithm estimates its new position using its velocity and constructs a box around the resulting point. The box, shown around the apples in Figure 3a, is sized such that it should still enclose the apple for any reasonably small time step. The positions of the enclosed points in the processed frame from Figure 2b are averaged to obtain the apple's new position, and the previous position is subtracted to obtain the new velocity. The process is then repeated using this updated information for the subsequent frame.

Two major problems arise using this simple approach. First, when two apples overlap, the tracker with the weaker signal tends to snap onto the other and lose its target. To prevent this, a condition is added such that when the centers of two apples pass within 100 pixels of each other, both trackers switch to a linear trajectory based on their recent velocities, allowing the trackers to remain roughly on the same trajectory as their respective targets during overlap events. After passing out of range, they revert to normal operation and snap back onto their respective targets.

Second, due to poor lighting and irregular coloration of the apples, the target signal occasionally becomes too weak for the tracker to remain locked, causing any small fluctuation in pixel values to draw it off course. Selecting the proper threshold in Equation 1 is critical for reducing this problem. In addition, if the



(a) (b)

Figure 3: Depiction of tracker locations overlaid on a) the original color image, and b) the time-difference image from Figure 2b.

sum total of pixel values contained within a tracker box falls below a certain threshold, the tracker will switch to a linear trajectory until the threshold is surpassed again, preventing it from being drawn off course by background signals. With these modifications and the appropriate parameter values, the algorithm is able to successfully track the apples over at least 618 frames, as shown in the final video.

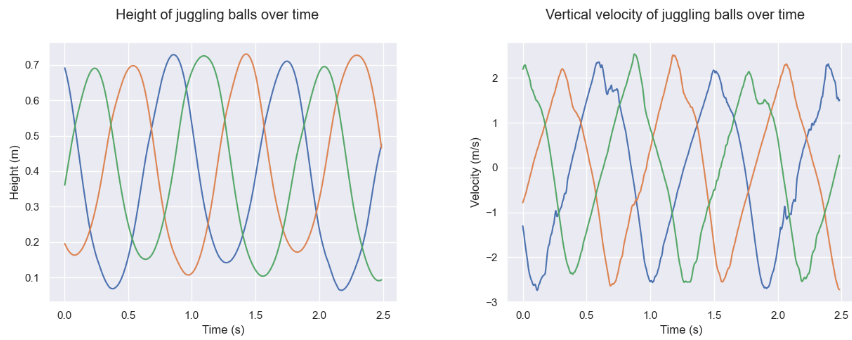
Despite its success, the level of fine-tuning required to circumvent the issues described above highlights the importance of beginning with robust data. With even lighting, uniform juggling balls, and a ball color more easily separated from the background, the analysis would likely have been simpler and more accurate.

4 Results

The position and velocity data for the three balls, with a boxcar average applied to smooth out noise, are plotted below in Figures 4 and 5.

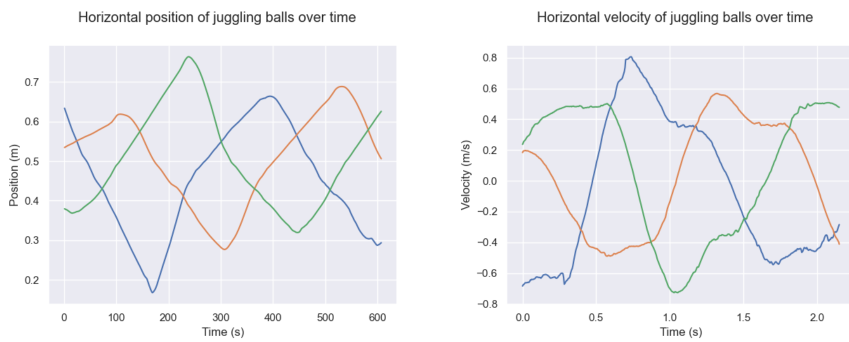
The vertical position plot in Figure 4 shows periodic curves with a peak-to-peak amplitude of roughly 0.5–0.6 m. The vertical velocity plot in Figure 4b shows a pattern roughly similar to a saw tooth wave, where the velocity decreases linearly for a time, undergoes a sharp change in acceleration, and increases linearly until another sharp turn repeats the cycle.

Physically, the periods of negative acceleration correspond to the ball's free trajectory through the air, while the periods of positive acceleration correspond to it being caught and thrown upward by the juggler. This interpretation agrees



(a) (b)

Figure 4: Plots of a) position and b) velocity in the vertical direction.



(a) (b)

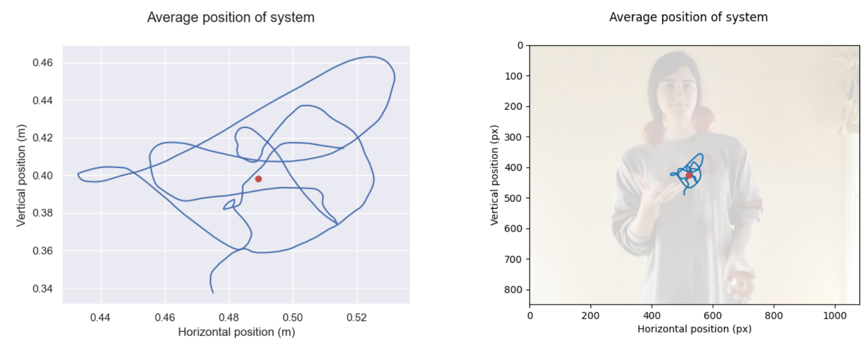
Figure 5: Plots of a) position and b) velocity in the horizontal direction.

with the position plot, which is best described as a series of parabolas with alternating concavity.

For the horizontal motion, the position plot in Figure 5a shows a rough saw tooth pattern, indicating that the balls travel roughly at a constant speed before undergoing a large acceleration and reversing direction. The velocity plotted in Figure 5b very roughly consists of periods of constant velocity connected by periods of large acceleration. This agrees with the physical interpretation, as the balls should maintain a constant horizontal velocity during free-fall.

An interesting feature visible in the peaks of the horizontal velocity curves is a brief period of negative acceleration (positive for green) followed by constant velocity, creating a "shoulder" effect. It likely indicates that as the juggler catches the ball and prepares to throw it upward, their hand moves with a horizontal velocity that is constant but slower than the ball being caught.

To examine the behavior of the system as a whole, the averaged position of the three-apple system at each time step is plotted in space in Figure 6, with the total average over time depicted by a red point. Figure 7 quantifies this by showing the distance of the system's position from the time-averaged center at each time step. The average deviation from the center is 3.0 cm, and the maximum displacement is around 7.2 cm. Based on Figure 6b, which plots the curve in the context of the full image, this corresponds to a region slightly larger than the apples being juggled.



(a) (b)

Figure 6: Plots showing the path of the system's average position over time, with the total average position denoted by a red point. Figure a) shows a detailed view of the path, while Figure b) shows the path in the larger context of the frame.

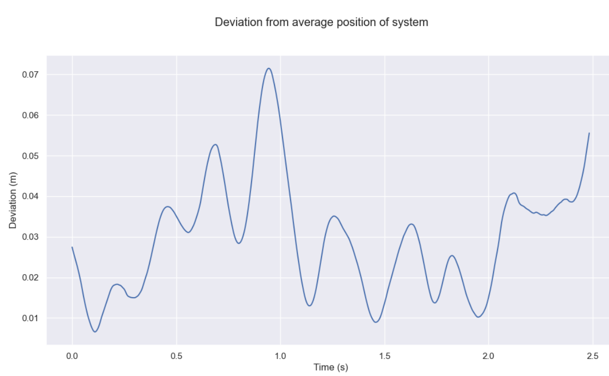


Figure 7: Plot of the deviation of the system's average position from the total average over time. Physically, this plot depicts the distance of the path in Figure 6a from the red dot at each point in time.

5 Conclusion

This report serves as a proof of concept for the use of video analysis in studying objects in motion. Filming a juggler at 240 frames per second, processing the frames to isolate the objects in question, and applying a tracking algorithm yielded a detailed picture of the positions and velocities of the juggling balls over time. The results are consistent with the expected alternation between periods of free-fall behavior and upward acceleration due to the juggler. A final video showing the original and processed frames (Figures 1 and 2) can be viewed here.

Although the analysis was successful as a proof of concept, there are a few aspects that should be improved in future applications. Acquiring a clear, uniformly lit video for the analysis is essential to extracting a reliable signal, as workarounds for poor data yield inferior results for additional effort. Furthermore, the objects being tracked should be uniformly colored and distinct from the background, if the experiment permits. Finally, taking advantage of more advanced object tracking algorithms available in packages such as OpenCV would improve the accuracy and reduce the effort required for the analysis.