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Video capture and post-processing technique for approximating 3D projectile trajectory

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Abstract

In this paper we introduce a low-cost procedure and methodology for markerless projectile tracking in three-dimensional (3D) space. Understanding the 3D trajectory of an object in flight can often be essential in examining variables relating to launch and landing conditions. Many systems exist to track the 3D motion of projectiles but are often constrained by space or the type of object the system can recognize (Qualisys, Göteborg, Sweden; Vicon, Oxford, United Kingdom; Opti-Track, Corvallis, Oregon USA; Motion Analysis, Santa Rosa, California USA; Flight Scope, Orlando, Florida USA). These technologies can also be quite expensive, often costing hundreds of thousand dollars. The system presented in this paper utilizes two high-definition video cameras oriented perpendicular to each other to record the flight of an object. A postprocessing technique and subsequent geometrically based algorithm was created to determine 3D position of the object using the two videos. This procedure and methodology was validated using a gold standard motion tracking system resulting in a 4.5 ± 1.8% deviation from the gold standard.

Keywords: projectile tracking, post processing, 3D trajectory, football flight

1. Introduction

Understanding the three-dimensional (3D) trajectory of an object in flight and its relationship to the environment can often be essential in examining variables relating to projectile launch and landing conditions. Drawbacks in existing technology include expense, accuracy, capture volume, and/or the versatility required to track diverse objects (e.g. soccer ball vs. football vs. baseball).

Robust technologies including infrared motion tracking and wireless sensors are commonly used but are often limited by capture volume and cost. Systems that utilize infrared require the object to display retro-reflective material. The addition of this material to the studied projectile may adversely affect its properties (i.e. stiffness or aerodynamics). These systems are limited to calibration volumes dictated by factors including number of cameras, camera orientation, and methods for calibrating the areas viewed by the cameras (Mündermann, Corazza, & Andriacchi, 2006). In most cases with these systems, a larger capture volume (volume in which the objected will be tracked) requires more equipment and can result in an increased error in measurement (Mündermann et al., 2006).

Wireless movement sensors (e.g. accelerometers and gyroscopes) provide a means for tracking 3D position and rotation of objects (Mathie, Coster, Lovell, & Celler, 2004). Beyond needing to instrument the ball being tracked, two data analysis challenges in obtaining accurate trajectory information when using movement sensors include the need for baseline information about the object's initial conditions (e.g. position, velocity, and/or orientation) and the tendency for sensor *drift* (Yun, Bachmann, Moore, & Calusdian, 2007). Additionally, care needs to be taken when adding material (sensors, power supplies, etc.) to the ball to ensure the ball is within allowed size, weight, and balance specifications by sporting officials. If not done correctly, the flight of the projectile (ball) can be drastically affected. Despite these challenges, sensors has been used successfully in a number of athletic balls such as soccer balls (i.e. the adidas® MiCoach

Smart Ball), basketballs (Abdelrasoul, Mahmoud, Stergiou, & Katz, 2015), cricket balls (Doljin & Fuss, 2015; Fuss, Ferdinands, Doljin, & Beach, 2014), and American footballs (Goldhammer, Chuang, Mullinix, et al., 2009).

A promising technique for automatic projectile tracking over a large distance is radio frequency (RF) tracking. In simulations, researchers have found that this methodology can track up to 150 m at a frequency reaching 240 Hz (Menache & Sturza, 2006). This technology is used in golf ball tracking since the ball can have a radio frequency identification chip implanted during manufacturing so that RF receivers can triangulate the ball's position (Flight Scope, Orlando, Florida USA). Again, this technology can be expensive and depending on the object being tracked, the addition of material may affect its aerodynamic properties.

Experimentation with computer vision has been performed with tracking many types of athletes such as swimmers (Trangbæk, Rasmussen, & Andersen, 2016) and soccer players (Xu, Orwell, Lowey, & Thirde, 2005). The use of computer vision greatly reduces equipment cost and has also been used in golf to track putter and ball movement on the green (Woodward & Delmas, 2005) as well as ball flight while approaching the green (Zupančič & Jaklič, 2009). The systems presented in these studies recreate the trajectory of the ball in 3D space. However, Woodward and Delmas' system is constrained to the ball rolling on the green and Zupančič and Jaklič's system is unable to track initial launch data but rather the end result of the ball landing.

The purpose of this study was to develop and validate an affordable procedure and post-processing method that uses computational methods to track the 3D trajectory of an American football from initial launch to landing. The requirements of this methodology included: (1) no alterations to object being tracked (e.g. addition of retro-reflective markers); and (2) a capture volume of 75 × 50 × 75 m or greater.

2. Methods

Due to its size and shape, a golf ball was selected as the initial projectile for algorithm development. One camera (Panasonic HC-V100, 1080p, 24 Hz), oriented perpendicular to the *x-axis* (Figure 1), produced data relevant to the projectile's motion along the *x-* and *z-axis* (longitudinal and vertical position). A second similar camera, oriented parallel to the *x-axis*, produced data relevant to the projectile's motion along the *y-axis* (lateral position). To evaluate the projectile's movement in the *y-direction,* a "sight triangle" was created using a set of calibration markers (40 × 10 mm) affixed to the ground .762 m apart along the *x-axis*. These markers were used to calibrate the video data in the *xz-plane*. A second equidistant set (in the *x-direction*) was placed .305 m apart in the *y-direction* for calibration of the camera directed down the *x-axis* (Figure 1).

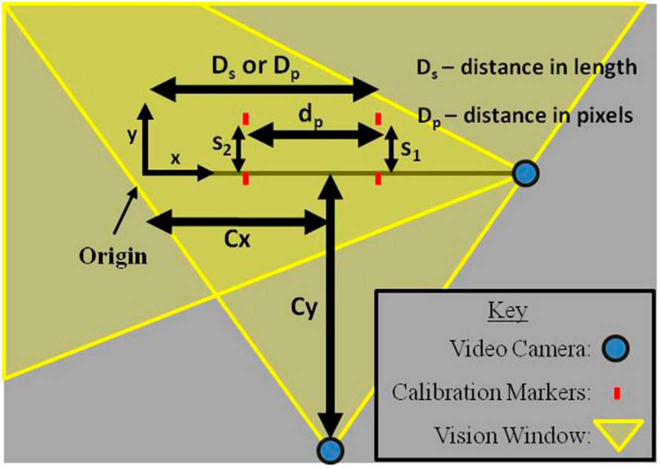


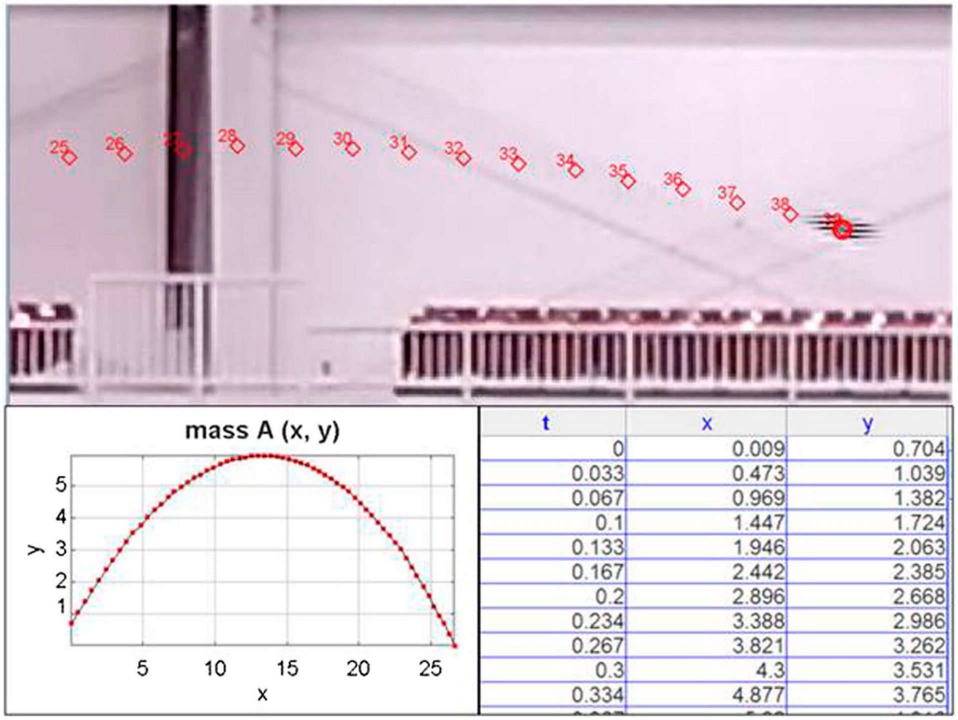
Figure 1. Data collection setup/explanation of variables.

An *uncompensated* two-dimensional (2D) motion trajectory of the golf ball's flight was calculated for each camera by measuring position with a pixel to distance ratio (Brown, 2015). Videos were uploaded into Tracker and the calibration markers (Figure 1) were used to calibrate distance in both 2D frames of motion (parallel and perpendicular camera views).

Both automatic and manual tracking options are available within the Tracker software. The automatic tracking is greatly influenced by the contrast between the projectile and video background. Background subtraction can be used to enhance contrast in stationary background conditions as stationary background objects are eliminated from the images. This process as Chien, Ma, and Chen (2002) explained in depth, results in a black image with a white projectile. However, the frame rate (24 Hz) used for this study resulted in the object blurring, thus detracting from the capacity to accurately track the projectile. Thus, for the purpose of this study, manual selection of the object in the frame was performed. Figure 2 depicts a snapshot of these data points on the video (top), position vs. time (bottom left), and table form (bottom-right) while tracking the flight of a football.

The 2D position data gathered from the two cameras were time-synched through identification of the ball to ground impact. The *x-position* and *z-position* were obtained from the camera perpendicular to the *x-axis* while the *y-position* was obtained from the camera parallel to the *x-axis*. This set of 3D Cartesian coordinates was referred to as the *uncompensated* position.

To accommodate for the distortion arising from out-of-plane motion for each camera, coordinate data were adjusted. The *y-position* was adjusted using methodology described in Equations (1)–(3):



t	x	y
0	0.009	0.704
0.033	0.473	1.039
0.067	0.969	1.382
0.1	1.447	1.724
0.133	1.946	2.063
0.167	2.442	2.385
0.2	2.896	2.668
0.234	3.388	2.986
0.267	3.821	3.262
0.3	4.3	3.531
0.334	4.877	3.765

Figure 2. Obtaining 2D position data through tracker (Brown, 2015).

$$y_i' = \frac{s_1 * (y_i - y_{c(i)})}{s_1 - y_{c(i)}} \tag{1}$$

$$y_{c(i)} = \frac{\dfrac{D_p * D_s}{s_1} - x_{p(i)}}{\dfrac{\frac{d_p * d_s}{s_1}}{s_1 - s_2}} \tag{2}$$

$$x_{p(i)} = \frac{D_p}{D_s} * x_i \tag{3}$$

where y_i was the *uncompensated y-position*, s_1 and s_2 were the distance between the two calibration markers in pixels from the view of the parallel camera (see Figure 1), $y_{c(i)}$ was the correcting *y-factor.* D_s was the physical distance from the origin of the reference frame to the furthest set of calibration markers, D_p was the distance from the origin of the reference frame to the furthest set of calibration markers in pixels from the view of the parallel camera, x_i was the *uncompensated x-position*, $x_{p(i)}$ was the x_i*-position* in pixels, d_s was the distance between the two sets of calibration markers, d_p was the distance d_s in pixels from the view of the parallel camera, and y_i' was the *compensated y-position*. A *compensated* position referred to an *uncompensated* position value that was altered with the presented algorithm.

Next, y_i' was used to calculate the *compensated z-position* and *x-position,* z_i' and x_i', respectively. These compensated positions were calculated using Equations (4) and (5):

$$z_i' = \frac{z_i - h}{C_y} * (Cy + y_i') + h \tag{4}$$

$$x_i' = C_x - (C_y + y_i') * \frac{C_x - x_i}{C_y} \tag{5}$$

where *h* was the viewing height of the camera (both cameras were leveled and positioned at the same height), C_y was the distance from the perpendicular camera to the *x–z plane* (see Figure 1), C_x was the longitudinal distance the perpendicular camera was from the coordinate origin, and z_i was the *uncompensated z-position*.

The presented algorithm was developed by creating a sight triangle in the parallel camera view to more properly account for the depth in the 2D image thus driving the equations determining the *compensated y-position.* Once the *compensated y-position* was determined, the geometric concept depicted in Figure 3 was used to calculate the *compensated z-position* in Equation (4). This same concept was then used to calculate the *compensated x-position* in Equation (5).

Algorithm validation was performed using a *gold standard* 3D motion analysis system (3 Qualisys Oqus 400 series cameras, 200 Hz, calibration residuals <1 mm). A golf ball (42.67 mm in diameter), covered with retro-reflective tape was simultaneously tracked during flight through a 3 × 3 × 3 m capture volume by the presented video-graphic procedure and the 3D motion capture technology. Ten

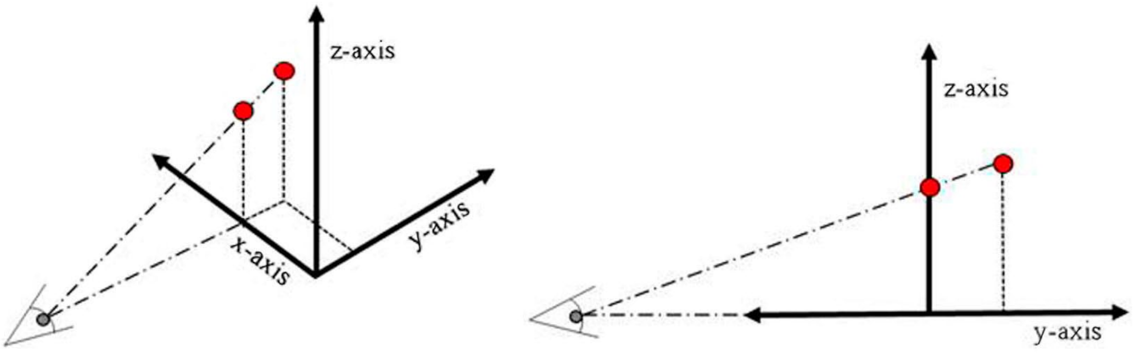


Figure 3. Geometric concept for compensating for the *z*-position.

Table 1. Average resultant deviation from the control for *uncompensated* and *compensated* position

	Measured position		Adjusted position	
	Error (mm)	Percent Error	Error (mm)	Percent Error
Trial 01	62.6	6.8%	39.0	4.2%
Trial 02	253.8	14.4%	88.0	5.0%
Trial 04	254.9	12.1%	140.3	6.7%
Trial 05	109.8	10.1%	47.2	4.3%
Trial 06	61.6	3.2%	50.1	2.6%
Trial 07	192.5	9.6%	40.8	2.0%
Trial 08	169.2	9.0%	70.0	3.7%
Trial 09	216.2	17.2%	96.9	7.7%
Trial 10	243.1	12.1%	88.6	4.4%
Average*	173.7	**10.5%**	73.4	**4.5%**
STDEV*	78.3	**4.1%**	33.5	**1.8%**

* Trial 03 was determined an outlier and is not included in the average and standard deviation calculations

repetitions were performed (Table 1). Note that the retro-reflective tape was not required for the proposed tracking system, but instead was required for the Qualisys tracking system.

3. Results

As expected, the *gold standard, uncompensated,* and *compensated* trajectories were not identical (Figure 4).

Using the presented procedure for video capture the *uncompensated* coordinate data resulted in an average percent deviation from the *gold standard* 3D trajectory of 10.5 ± 4.1% (Table 1). After applying the presented geometrical adjustment technique, the average percent deviation of the *compensated* from the *gold standard* trajectory reduced to 4.5 ± 1.8% (Table I).

4. Discussion

This study describes development and validation of a geometric triangulation algorithm that enables affordable tracking of diverse objects in 3D space using only two inexpensive video cameras and four calibration markers. The use of this methodology increases capture volume (common issue in IR motion tracking systems), removes the need to add materials or sensors to the projectile (removing complications with regards to regulated size, weight, and balance specifications), and reduces the cost of projectile tracking (i.e. price of instrumented balls, IR camera systems).

When assessed relative to the *gold-standard* (e.g. Qualisys motion analysis system, Göteborg, Sweden), the *compensated* technique resulted in a 57% decrease in error compared to the *uncompensated* approach when tracking golf ball trajectory. The error presented relates to the average overall error in the trajectory with respect to the horizontal distance traveled by the projectile. Factors that may have contributed to error include accurate placement of calibration markers, and camera orientation. Calibration markers should be positioned accurately and the cameras must be properly directed to clearly view the perpendicular *xz*- and *yz-planes* to obtain the most precise position measurements.

The low frame rate (24 Hz) of the 2D cameras used in the current study resulted in projectile blurring in a number of frames. In these instances the center of the blurred projectile was approximated and assessed as the data point. This is a limitation in the presented study that

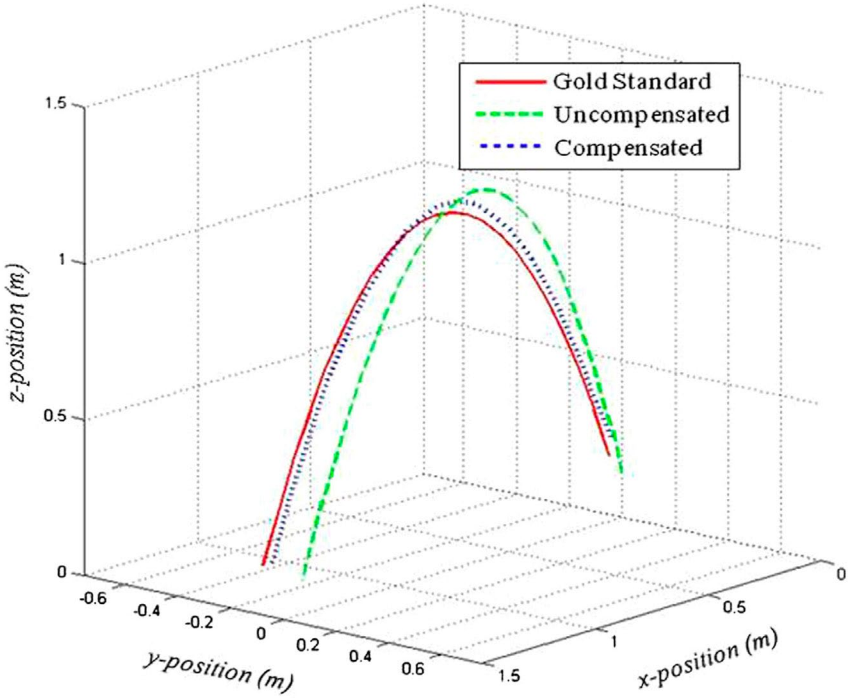
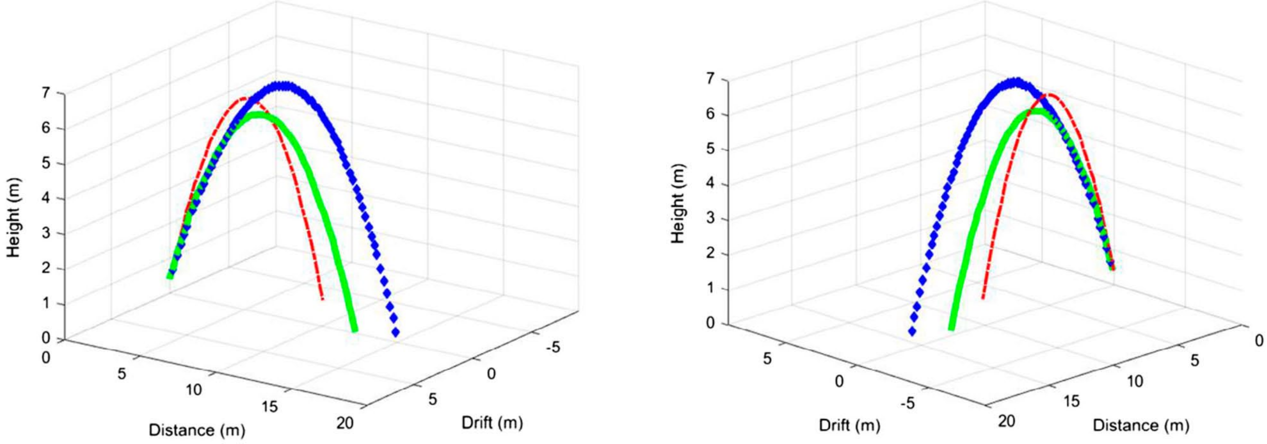


Figure 4. Example result displaying the *Gold Standard, Uncompensated,* and *Compensated* trajectories (Trial 05).



(a) Impact 3cm from the bottom of the ball - Left Iso

(b) Impact 3cm from the bottom of the ball - Right Iso

(c) Height v. Distance - Impact 3cm from the bottom of the ball

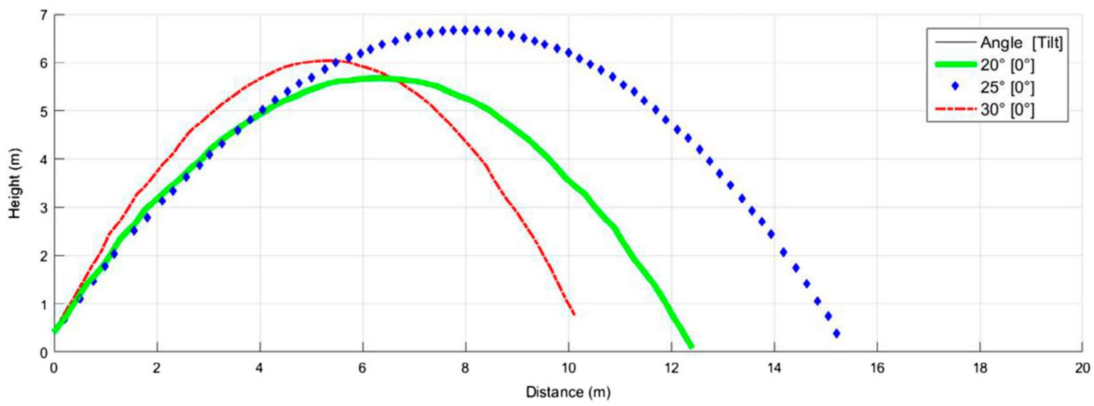


Figure 5. Example football trajectories.

contributes to the average error. Though it has not yet been experimentally tested, we expect that cameras recording at a higher frequency would reduce the amount of error resulting from video processing and time-based compiling.

In summary, this work developed and validated an affordable (estimated at ~$400), accurate (<5% average error) technology for tracking 3D ball flight from launch to landing. Current work is aimed at utilizing this system to investigate the flight of a football.

5. Future directions

The presented procedure and methodology for projectile tracking is currently being used to track the trajectory of a football's flight over a distance up to 25 m and a height up to 7 m. Human observations and measurements of landing location as well as video confirmation has shown that this procedure can successfully be used when tracking the trajectory of a football over larger capture volume. Thus, the presented low-cost system allows for the investigation of football flight after being impacted under different conditions.

The presented procedure and methodology allows for the examination of projectiles in flight without the addition of materials to the object, and largely reduces constraints in capture volume. As an example, nine trajectories are presented in Figure 5 corresponding to a football being impacted with varied ball orientation and angle of impact. Other potential advancements include developing a program to help automate this process. It would allow for two videos of perpendicular views to be uploaded, calibration markers to be identified, and the ball to be tracked manually or automatically. Such a program would be similar to that of Brown's Tracker software but would require a number of additional calibration steps and utilize the presented algorithm to output an accurate 3D projectile trajectory.

The keys in Figure 5 refer to the angle of impact by a mechanical field-goal kicker and the angle in which the ball was tilted pre-impact. For example "20° [0°]" refers to a football flight trajectory where the impactor strikes the ball at a 20° angle while the ball is oriented vertically (0°). In some cases, the ball was also tilted 15° to the left (20° [L15°]) or right (20° [R15°]).

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