

Paradoxical pop-ups: Why are they difficult to catch?

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Professional baseball players occasionally find it difficult to gracefully approach seemingly routine pop-ups. We describe a set of towering pop-ups with trajectories that exhibit cusps and loops near the apex. For a normal fly ball the horizontal velocity continuously decreases due to drag caused by air resistance. For pop-ups the Magnus force is larger than the drag force. In these cases the horizontal velocity initially decreases like a normal fly ball, but after the apex, the Magnus force accelerates the horizontal motion. We refer to this class of pop-ups as paradoxical because they appear to misinform the typically robust optical control strategies used by fielders and lead to systematic vacillation in running paths, especially when a trajectory terminates near the fielder. Former major league infielders confirm that our model agrees with their experiences. © 2008 American Association of Physics Teachers.

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I. INTRODUCTION

Baseball has a rich tradition of misjudged pop-ups. For example, on April, 1961, Roy Sievers of the Chicago White Sox hit a towering pop-up above Kansas City Athletics' third baseman Andy Carey who fell backward trying to make the catch. The ball landed several feet from third base, far out of the reach of Carey. It rolled into the outfield, and Sievers wound up on second with a double.

Some other well-known misplays of pop-ups include New York Giants first baseman Fred Merkle's failure to catch a foul pop-up in the final game of the 1912 World Series, costing the Giants the series against the Boston Red Sox; St. Louis first baseman Jack Clark's botched foul pop-up in the sixth game of the 1985 World Series against Kansas City; and White Sox third baseman Bill Melton's broken nose suffered in an attempt to catch a "routine" pop-up in 1970.

As seen by these examples, even experienced major league baseball players can find it difficult to position themselves to catch pop-ups hit very high over the infield. Players describe these batted balls as "tricky" or "deceptive," and at times they are seen lunging for the ball at the last instant of the ball's descent. "Pop-ups look easy to anyone who hasn't tried to catch one—like a routine fly ball that you don't have to run for," Clete Boyer said, "but they are difficult to judge and can really make you look like an idiot."¹ Boyer, a veteran of 16 years in the major leagues, was considered one of the best defensive infielders in baseball.

Several factors can exacerbate an infielder's problem of positioning himself for a pop-up. Wind currents high above the infield can change the trajectory of a pop-up radically. Also, during day games the sky might provide little contrast as a background for the ball—a condition called a "high sky" by players. Then, there are obstacles on the field—bases, the pitcher's mound, and teammates—which can hinder the infielder. But even on a calm night with no obstacles nearby, players might stagger in their efforts to get to the ball.

The frequency of pop-ups in the major leagues—an average of nearly five pop-ups per game²—is sufficiently large that teams provide considerable pop-up practice for infielders and catchers. Yet, this practice does not improve the skill of these players, and they are unable to reach the level of competency in catching "sky-high" pop-ups that outfielders attain in catching high fly balls, for example. This inability suggests that the technique commonly used to catch pop-ups might be the factor limiting improvement.

Almost all baseball players learn to catch low, "hump-back" pop-ups and fly balls before they have any experience in catching lofty pop-ups. In youth leagues nearly all pop-ups have low velocities and few exceed a height of 50 feet; therefore, they have trajectories that are nearly parabolic. Fly balls, too, have near-parabolic trajectories. Our hypothesis is that 120' pop-ups do not follow similar trajectories, and hence major league infielders find pop-ups difficult to catch because the tracking and navigation method they learned in their youth is unreliable for high, major league pop-ups.

To consider this hypothesis we first describe the trajectories of prototypical batted balls, using models of the bat-ball collision and ball flight aerodynamics. We then develop models of three kinds of typical nonparabolic pop-up trajectories that exhibit unexpected behavior around their apices, including cusps and loops. Several of these trajectories are fitted using an optical control model that has been used successfully to describe how players track fly balls. For each fit a prediction of the behavior of infielders attempting to position themselves to catch high pop-ups is compared with the observed behavior of players during games.

II. SIMULATIONS OF BATTED-BALL TRAJECTORIES

As students in an introductory physics course learn, the trajectory of a fly ball in a vacuum is a symmetric parabola because the only force acting on it is gravity. In the atmo-

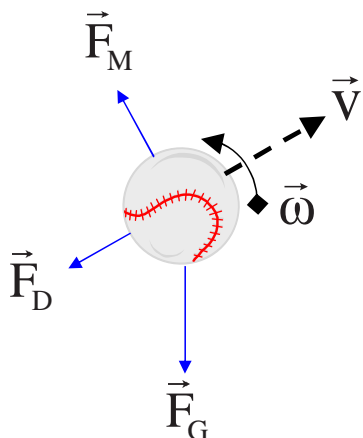


Fig. 1. The forces on a baseball in flight with backspin, including gravity F_G , drag F_D , and the Magnus force F_M . F_D acts in the $-\hat{v}$ direction and F_M acts in the $\hat{\omega} \times \hat{v}$ direction.

sphere the ball is subject to additional forces as shown schematically in Fig. 1: the retarding drag force F_D and the Magnus force F_M . The Magnus force was first mentioned in the literature by a young Isaac Newton in his treatise on the theory of light,³ where he included a brief description of the curved trajectory of a spinning tennis ball. Whereas the drag force always acts opposite to the instantaneous direction of motion, the Magnus force is normal to both the velocity and spin vectors. For a typical fly ball to the outfield the drag force causes the trajectory to be somewhat asymmetric, with the falling angle steeper than the rising angle,⁴ although the trajectory is still smooth. If the ball has backspin, as expected for such fly balls, the Magnus force is primarily in the upward direction, resulting in a higher but still quite smooth trajectory. We will show that the trajectory is qualitatively different for a pop-up, because a ball-bat collision resulting in a pop-up will have considerable backspin, resulting in a significantly larger Magnus force than for a fly ball. Moreover, the direction of the force is primarily horizontal and is opposite on the upward and downward paths. These conditions will result in unusual trajectories, sometimes with cusps and loops.

The collision model is identical to that used by Sawicki, Hubbard, and Stronge⁵ and by Cross and Nathan.⁶ The geometry of the collision is shown in Fig. 2. A standard base-

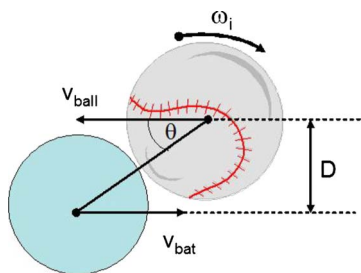


Fig. 2. Geometry of the ball-bat collision. The initial velocity of the ball and bat are v_{ball} and v_{bat} , respectively, and the pitched ball has backspin of magnitude ω_i . The bat-ball offset shown in the figure is denoted by $D = (r_{\text{ball}} + r_{\text{bat}})\sin\theta$, where r_{ball} and r_{bat} are the radii of the ball and bat, respectively. For the collisions discussed in the text, the entire picture should be rotated counterclockwise by 8.6° , so that the initial angle of the ball is 8.6° downward and the initial angle of the bat is 8.6° upward.

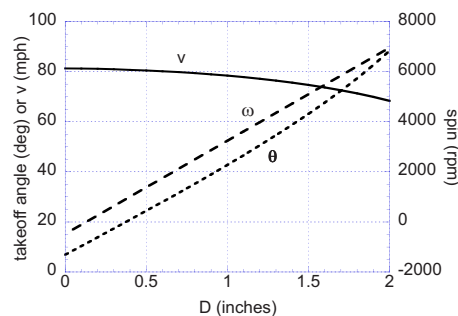


Fig. 3. Variation of the batted ball speed, initial angle above the horizontal, and spin with the offset D .

ball ($r_{\text{ball}}=1.43$ in., mass=5.1 oz) approaches the bat with an initial speed $v_{\text{ball}}=85$ mph, initial backspin $\omega_i=126$ rad/s (1200 rpm), and a downward angle of 8.6° (not shown in the figure). The bat has an initial velocity $v_{\text{bat}}=55$ mph at the point of impact and an initial upward angle of 8.6° , which is identical to the downward angle of the ball. The bat is a 34-in.-long, 32 oz wood bat, with radius $r_{\text{bat}}=1.26$ in. at the impact point. If lines passing through the center of the ball and bat are drawn parallel to the initial velocity vectors, these lines are offset by the distance D . This distance is the amount by which the bat undercuts ($D>0$) or overcuts ($D<0$) the ball. In the absence of initial spin on the baseball, a head-on collision ($D=0$) results in the ball leaving the bat at an upward angle of 8.6° with no spin; undercutting the ball produces backspin and a larger upward angle; overcutting the ball produces topspin and a smaller upward or even a downward angle. The initial backspin on the pitched ball does not change these qualitative features. The ball-bat collision is characterized by the normal and tangential coefficients of restitution, e_N and e_T , respectively, with the additional assumption that angular momentum is conserved about the initial contact point between the ball and bat.⁶ For e_N we use the parametrization

$$e_N = 0.54 - (v_N - 60)/895, \quad (1)$$

where $v_N = (v_{\text{ball}} + v_{\text{bat}})\cos\theta$ is the normal component of the relative ball-bat velocity in units of mph.⁵ We further assume that $e_T=0$, which is equivalent to assuming that the tangential component of the relative ball-bat surface velocity, which is initially equal to $(v_{\text{ball}} + v_{\text{bat}})\sin\theta + \omega_i r_{\text{ball}}$, is identically zero as the ball leaves the bat. This value of e_T implies that the ball leaves the bat in a rolling motion. The loss of tangential velocity occurs as a result of sliding friction. It was verified by direct calculation that the assumed coefficient of friction of 0.55⁶ is sufficient to bring the tangential motion to a halt prior to the end of the collision for all values of $D < 1.7$ in. Given the initial velocities and our assumptions about e_N and e_T , the outgoing velocity v , angle θ , and the backspin ω of the baseball can be calculated as a function of the offset D . These parameters, which are shown in Fig. 3, along with the initial height of 3 feet, serve as input to the calculation of the batted-ball trajectory. Note in particular that both ω and θ are strong functions of D , and v depends only weakly on D .

The trajectory of the batted baseball is calculated by numerically solving the differential equations of motion using a

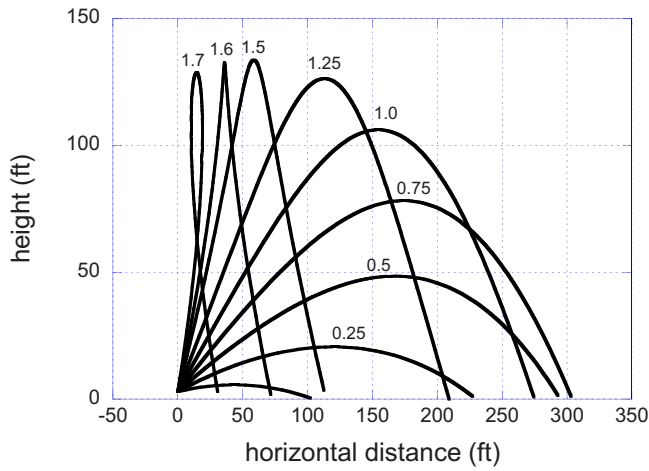


Fig. 4. Simulated trajectories of pop-ups, fly balls, and line drives with drag and spin-induced forces. These trajectories were produced when an 85 mph fastball with 1200 rpm backspin collided with the sweet spot of a bat moving at 55 mph. Each trajectory was created by a different offset D (in inches, indicated near the apex of each trajectory) between the bat and ball, as defined in Fig. 2.

fourth-order Runge-Kutta technique, given the initial conditions and the forces. The drag and Magnus forces are usually written as

$$\vec{F}_D = -\frac{1}{2}C_D\rho Av^2\hat{v}, \quad (2)$$

$$\vec{F}_M = \frac{1}{2}C_L\rho Av^2(\hat{\omega} \times \hat{v}), \quad (3)$$

where ρ is the air density (0.077 lb/ft³), A is the cross sectional area of the ball (6.45 in., Ref. 2), v is the velocity, ω is the angular velocity, and C_D and C_L are phenomenological drag and lift coefficients, respectively. Note that the direction of the drag is opposite to the direction of motion, and the direction of the Magnus force is determined by a right-hand rule. We utilize the parametrizations of Ref. 5 in which C_D is a function of the speed v and C_L is a bilinear function of the spin parameter $S=r_{\text{ball}}\omega/v$, implying that F_M is proportional to ωv . Because the velocity of the ball does not remain constant during the trajectory, it is necessary to compute C_D and C_L at each point in the numerical integration. The resulting trajectories are shown in Fig. 4 for values of D in the range 0–1.7 in., where an initial height of 3 ft. was assumed.

The striking feature of Fig. 4 is the qualitatively different character of the trajectories as a function of D , or equivalently as a function of the takeoff angle θ . These trajectories range from line drives at small θ , to fly balls at intermediate θ , to pop-ups at large θ . Particularly noteworthy is the rich and complex behavior of the pop-ups, including cusps and loops. We focus on two characteristics that may have implications for the algorithm used by a fielder to catch the ball: the symmetry/asymmetry about the apex and the curvature.

Before proceeding, we note that the general features of the trajectories shown in Fig. 4 are universal and do not depend on the particular model used for either the ball-bat collision or for the drag and lift. For example, using collision and aerodynamics models significantly different from those used

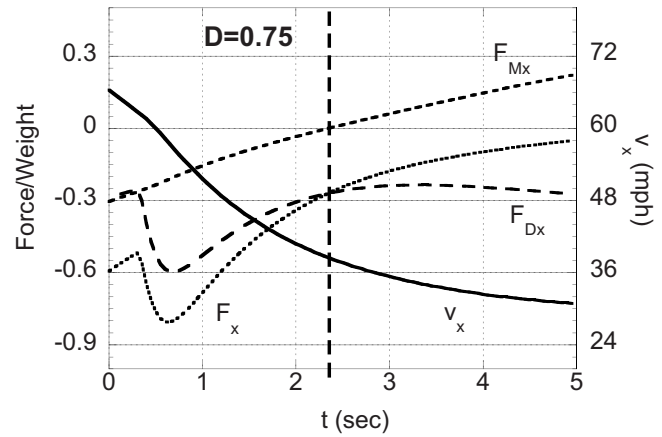


Fig. 5. Time dependence of the horizontal velocity, v_x , and the horizontal forces for the $D=0.75$ in. trajectory, typical of a long fly ball. The drag, lift, and total forces are denoted by F_{Dx} , F_{Mx} , and F_x , respectively, normalized to the weight. The vertical dashed line indicates the time that the apex is reached.

here, Adair finds similar trajectories with both cusp-like and loop-like behavior.⁴ Models based on equations in Watts and Bahill¹⁰ result in similar trajectories.

We first examine the symmetry or lack thereof of the trajectory about the apex. Without the drag and Magnus forces, all trajectories would be symmetric parabolas. The actual situation is more complicated. As seen in Fig. 4, baseballs hit at low and intermediate θ (line drives and fly balls) have an asymmetric trajectory, with the ball covering less horizontal distance on the way down than it did on the way up. This feature is known intuitively to experienced outfielders. For larger θ the asymmetry is smaller, and pop-ups hit at a very steep angle are nearly symmetric. How do the forces conspire to produce these results?

We address this question by referring to Figs. 5 and 6 in which the time dependence of the horizontal components of the velocity and the forces are plotted for a fly ball ($D=0.75$ in., $\theta=33^\circ$) and a pop-up ($D=1.6$ in., $\theta=68^\circ$). The initial decrease of the drag force for early times is due to the particular model used for the drag coefficient, which experiences a sharp drop near 75 mph. The asymmetry of the tra-

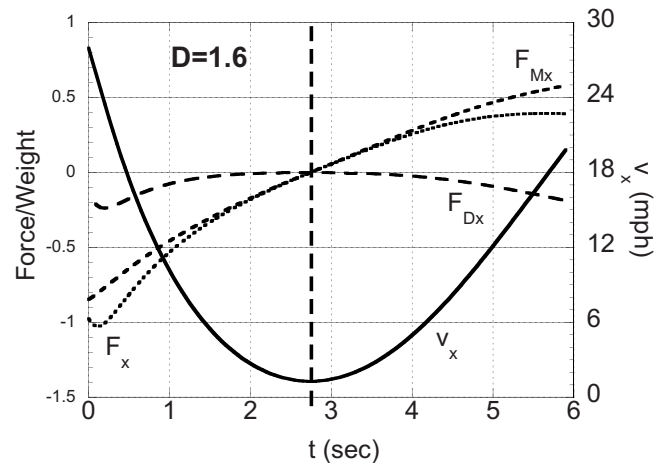


Fig. 6. Time dependence of the horizontal velocity, v_x , and the horizontal forces for the $D=1.6$ in. trajectory, typical of a high pop-up.

jectory depends on the interplay between the horizontal components of the drag and Magnus forces, F_{Dx} and F_{Mx} . For forward-going trajectories ($v_x > 0$), F_{Dx} always acts in the $-x$ direction, in contrast to F_{Mx} which acts in the $-x$ or $+x$ direction on the rising or falling part of the trajectory, respectively. The relative magnitudes of F_{Dx} and F_{Mx} depend strongly on θ and ω . For fly balls θ and ω are small enough (see Fig. 3) that the magnitude of F_{Dx} is generally larger than the magnitude of F_{Mx} , as shown in Fig. 5. Therefore F_x is negative throughout the trajectory. For such conditions there is a smooth continuous decrease in v_x , leading to an asymmetric trajectory, because the horizontal distance covered prior to the apex is greater than that covered after the apex. The situation is qualitatively different for pop-ups, because both θ and ω are significantly larger than for a fly ball. As a result, the magnitude of F_{Mx} is much greater than the magnitude of F_{Dx} . Figure 6 shows that $F_x \approx F_{Mx}$, so that F_x acts in the $-x$ direction before the apex and in the $+x$ direction after the apex. Therefore, the loss of v_x while rising is largely compensated by a gain in v_x while falling, resulting in near symmetry about the apex. Moreover, for this particular trajectory the impulse provided by F_x while rising is nearly sufficient to bring v_x to zero at the apex, resulting in cusp-like behavior. For even larger values of θ , F_x is so large that v_x changes sign prior to the apex, then reverses sign again on the way down, resulting in the loop pattern.

We next address the curvature of the trajectory, $C \equiv d^2y/dx^2$, which is determined principally by the interplay between the Magnus force F_M and the component of gravity normal to the trajectory $F_{GN} = F_G \cos \theta$. It is straightforward to show that C is proportional to the instantaneous value of $(F_M - F_{GN})/(v_x^2 \cos \theta)$ and in particular that the sign of C is identical to the sign of $F_M - F_{GN}$. In the absence of a Magnus force, the curvature is always negative, even if drag is present. An excellent example is provided by the inverted parabolic trajectories expected in the absence of aerodynamic forces.

The trajectories shown in Fig. 4 fall into distinct categories, depending on the initial angle θ . For small enough θ , C is negative throughout the trajectory. If C is initially negative, then it is always negative, because F_M is never larger and F_{GN} is never smaller than it is at $t=0$. For our particular collision and aerodynamic model, the initial curvature is negative for θ less than about 45° . For intermediate θ , C is positive at the start and end of the trajectory, but experiences two sign changes, one before and one after the apex. The separation between the two sign changes decreases as θ increases, until the two values coalesce at the apex, producing a cusp. For larger values of θ , C is positive throughout the trajectory, resulting in loop-like behavior such as the $D = 1.7$ in. trajectory, where the sign of v_x is initially positive, then changes to negative before the apex, and finally changes to back positive after the apex.

All the simulations discussed so far assume that the spin of the baseball remains constant throughout the trajectory. Because the spin plays such a major role in determining the character of the trajectory, it is essential to examine the validity of that assumption. To our knowledge there have been no experimental studies on the spin decay of baseballs, but there have been two such studies for golf.^{7,8} In Ref. 8 a model was proposed for the spin decay of a golf ball in which the torque responsible for the decay is expressed as $R\rho AC_M v^2$, where R is the radius of the ball, $C_M = \beta R\omega/v$ is

the ‘‘coefficient of moment,’’ and β is a dimensionless constant expressing the proportionality of C_M to $R\omega/v$. By equating the torque to $I d\omega/dt$, where $I = 0.4MR^2$ is the moment of inertia, the spin decay constant τ can be expressed as

$$\tau \equiv \frac{1}{\omega} \frac{d\omega}{dt} = \left[\frac{M}{R^2} \right] \frac{0.4}{\pi\rho\beta v}. \quad (4)$$

In Ref. 8 measurements of τ were used to determine $\beta \approx 0.012$, corresponding to $\tau = 20$ s for $v = 100$ mph. The measurements in Ref. 7 can be similarly interpreted with $\beta = 0.009$, corresponding to $\tau = 25$ s at 100 mph. To estimate the spin decay constant for a baseball, we assume Eq. (4) applies, with M/R^2 appropriately scaled for a baseball and with all other factors the same. Using $M/R^2 = 2.31$ and 2.49 oz/in.² for a golf ball and baseball, respectively, the decay time for a baseball is about 8% longer than for a golf ball, or 22–27 s at 100 mph and longer for smaller v . A similar time constant for baseball was estimated in Ref. 9 possibly using the same arguments as we have used here. Because the trajectories we have examined are in the air 7 s or less, we conclude that our results are not affected by spin decay. Adair⁴ has suggested a much smaller decay time of order 5 s, which does not seem to be based on experimental data. A direct check of our calculations shows that the qualitative effects depicted in Fig. 4 persist even with a decay time as short as 5 s.

III. OPTICAL CONTROL MODEL FOR TRACKING AND NAVIGATING BASEBALLS

In a seminal article Chapman¹¹ proposed an optical control model for catching fly balls, today known as optical acceleration cancellation (OAC). Chapman examined the geometry of catching from the perspective of a moving fielder observing an approaching ballistic target that is traveling along a parabola. He showed that in this case, the fielder can be guided to the destination by selecting a running path that keeps the image of the ball rising at a constant rate in a vertical image plane. Mathematically, the tangent of the vertical optical angle to the ball increases at a constant rate. When balls are headed to the side, other optical control strategies become available.^{12,13} We will consider balls hit directly toward the fielder, so we will emphasize predictions of the OAC control mechanism.

Chapman assumed parabolic trajectories because of his (incorrect) belief that the drag and Magnus forces have a negligible effect on the trajectory. We now know that the effects of these forces can be considerable, as discussed in Sec. II. Nevertheless, numerous perception-action catching studies confirm that fielders appear to utilize Chapman’s type of optical control mechanism to guide them to interception, and in particular OAC is the only mechanism that has been supported for balls headed in the sagittal plane directly toward fielders.^{12,14–16} Further support for OAC has been found with dogs catching Frisbees as well as functioning mobile robots.^{13,17}

Extensive research on the navigational behavior of baseball players supports that perceptual judgment mechanisms used during fly ball catching can generally be divided into two phases.^{12,18} During the first phase, while the ball is still relatively distant, ball location information is largely limited to the optical trajectory (that is, the observed trajectory path of the image of the ball). During the second phase, other cues

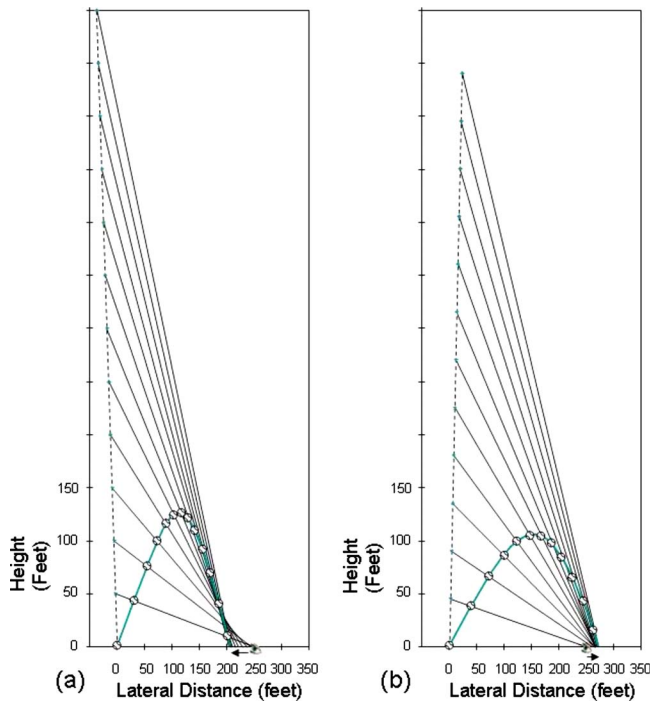


Fig. 7. Optical acceleration cancellation (OAC) with moving fielders and realistically modeled trajectories as the interception control mechanism for moving fielders. The outfielder starts at a distance of 250 ft from home plate. OAC directs the fielder to approach the desired destination along a smooth, monotonic running path. Shown are side views of the ball moving from left to right, and the fielder moving from the picture of eyeball at the right. The left diagram is the case of OAC directing fielder forward to catch a $D=1.25$ in. trajectory. The right diagram is the case of OAC directing fielder backward to catch a $D=1.0$ in. trajectory. In both cases, OAC produces a near constant running velocity along the path to the ball.

such as the increase in optical size of the ball and the stereo angle between the two eyes also become available and provide additional information for final corrections in fielder positioning and timing. The control parameters in models like OAC are optical angles from the fielder's perspective, which help direct the fielder's position relative to the ongoing ball position. Considerable work exploring and examining the final phase of catching has been done by perception scientists^{19,20} and some recent speculation has been done by physicists.²¹ It is generally agreed that the majority of fielder movement while catching balls takes place during the first phase in which fielders approach the destination region where the ball is headed. We focus here on control models like OAC that guide fielder position during the initial phase of catching. Thus for example, we would consider the famous play in which Jose Canseco allowed a ball to bounce off his head for a home run to be a catch, in that he was guided to the correct location to intercept the ball.

An example of how a fielder utilizes the OAC control strategy to intercept a routine fly ball to the outfield is given in Fig. 7. This figure illustrates the side view of a moving fielder using OAC control strategy to intercept two realistic outfield trajectories determined by our aerodynamics model described in Sec. II. As specified by OAC, the fielder runs forward or backward as needed to keep the tangent of the vertical optical angle to the ball increasing at a constant rate. Because the trajectory deviates from a parabola, the fielder compensates by altering his/her running speed. Geometri-

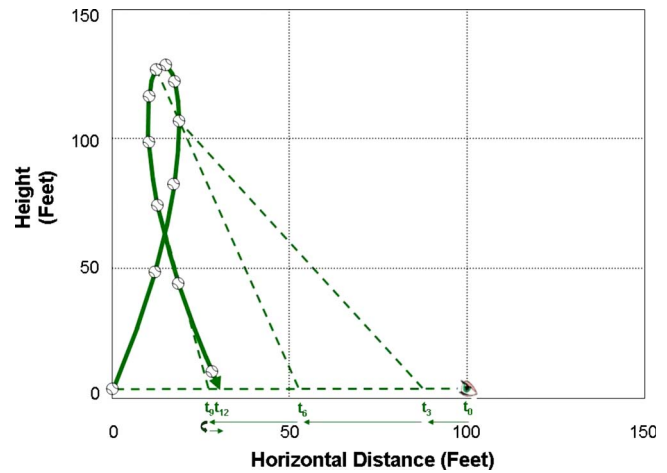


Fig. 8. Side view of the horizontal and vertical trajectory of a pop-up being fielded by the third baseman as seen by the first baseman. The dashed lines show the third baseman's gaze from his present position to the ball's present position. The balls show the trajectory at half-second increments. The "eye" shows the fielder's position at the start of the trajectory. The fielder moves in the direction shown by the arrows and exhibits little change in direction with a brief back turn near the end. This trajectory is for a $D=1.7$ in. pop-up.

cally the OAC solution can be described as the fielder keeping the image of the ball rising at a constant rate along a vertical projection plane that moves forward or backward to remain equidistant to the fielder. For fly balls such as that shown in Fig. 7, the geometric solution is roughly equivalent to the fielder moving in space to keep the image of the ball aligned with an imaginary elevator that starts at home plate and is tilted forward or backward by the amount corresponding to the distance that the fielder runs. As can be seen in Fig. 7 these outfield trajectories are notably asymmetric, principally due to air resistance, yet OAC still guides the fielder along a smooth, monotonic running path to the desired destination. This simple, relatively direct navigational behavior has been observed in almost all previous perception-action catching studies with humans and animals.¹⁷

Most models of interceptive perception-action assume that real-world fly ball trajectories remain sufficiently similar to parabolic for robust optical control strategies like OAC to produce simple, monotonic running path solutions. Supporting tests have confirmed simple behavior consistent with OAC in relatively extreme interception conditions including catching curving Frisbees, towering outfield blasts, and short infield pop-ups.^{12,13,15-17} We have shown that there is a class of paradoxical high infield pop-ups which deviate from normal parabolic shape in ways dramatic enough to lead fielders using OAC to head off in the wrong direction or bob forward and back. In the following we illustrate how a fielder guided by OAC will behave with the three paradoxical pop fly trajectories that we discussed in Sec. II.

We first examine the most extreme paradoxical trajectory of the group, the case of $D=1.7$ in. shown in Fig. 8. This trajectory does a full loop between the catcher and pitcher, finally curving back out on its descent and landing about 30 ft from home plate. Given the extreme directional changes of this trajectory, we might expect an infielder beginning 100 ft from home plate to experience difficulty achieving graceful interception. Yet, as can be seen Fig. 8, this case results in a relatively smooth running path solution. When the fielder maintains OAC throughout his approach, he

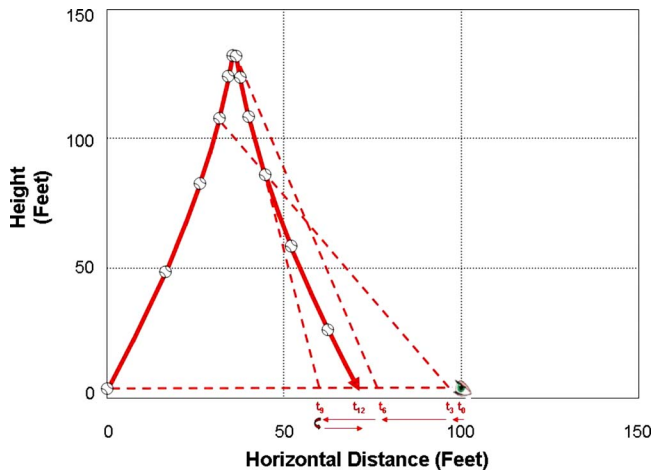


Fig. 9. Side view of a fielder using OAC to run up to a pop fly from the $D=1.6$ in. condition. In this case the fielder dramatically changes direction near the end.

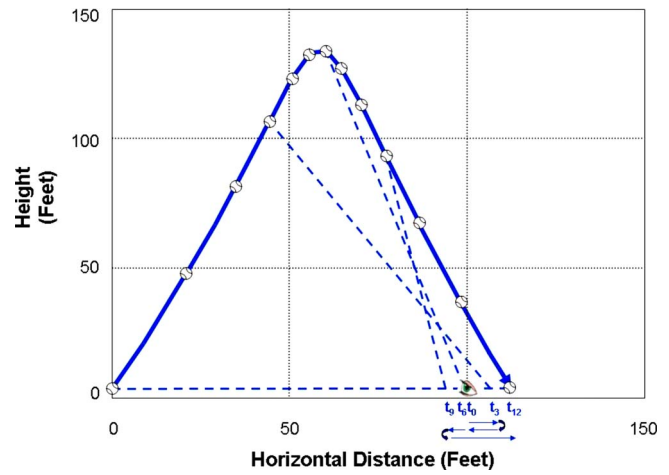


Fig. 10. Side view of a fielder using OAC to run up to a pop fly from the $D=1.5$ in. condition. The fielder changes direction twice, initially heading back, then forward, and finally back again.

initially runs quickly forward, then slightly overshoots the destination, and finally lurches back. In practice, near the interception point, the fielder is so close to the approaching ball that it is likely that the availability of other depth cues like stereo disparity and the rate of change in the optical size of the ball will mitigate any final lurch, and result in a fairly smooth overall running path to the destination.

Second we examine the case of a pop fly resulting from the bat-ball offset $D=1.6$ in. in Fig. 9. Here the horizontal velocity initially decreases and approaches zero velocity near the apex. Then after the apex the Magnus force increases the horizontal velocity. Of greater impact to the fielder is that this trajectory's destination is near where the fielder begins. Thus from the fielder's perspective, the trajectory slows in the depth direction before the discontinuity takes place such as to guide the fielder to run up too far and then later to reverse course and backtrack to where the ball is now accelerating forward. In this case the normally reliable OAC strategy leads the fielder to run up too far and in the final second lurch backward.

We next examine a pop fly that lands just beyond the fielder, the $D=1.5$ in. condition in Fig. 10. In this case OAC leads the fielder to initially head back to very near where the ball eventually lands, but then soon after change direction and run forward, only to have to run back again at the end. When a fielder vacillates or "dances around" this much, it does not appear that he is being guided well to the ball destination. Yet, this seemingly misguided movement is specified by the OAC control mechanism. Thus, the assumption that fielders use OAC leads to the prediction that even experienced, professional infielders are likely to vacillate and make a final lurch backward when navigating to catch some high pop-ups. Former major league infielders have affirmed to us that pop-ups landing at the edge of the outfield grass (100–130 ft from home plate) are the most difficult to catch.

It is notable that in each of the cases depicted in Figs. 8–10, the final movement by the fielder prior to catching the ball is backward. This feature can be directly attributed to the curvature of the trajectory, as discussed in Sec. II. For a typical fly ball the curvature is small and negative, so the ball breaks slightly toward home plate as it nears the end of its trajectory. For pop-ups the curvature is large and positive, so

the ball breaks away from home plate, forcing the fielder to move backward just prior to catching the ball.

IV. SUMMARY

Using models of the bat-ball collision and ball flight aerodynamics, we have shown that the trajectories of pop-ups can have unexpected features, such as loops and cusps. We examined the running paths that occur with these dramatically nonparabolic trajectories when a fielder utilizes optical acceleration cancellation, a control strategy that has been shown to be effective for tracking near-parabolic trajectories. We found that utilizing this strategy for these unusual pop-ups does not always lead to a smooth running path to intercept the ball.

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¹ Clete Boyer (private communication), 2007.

² Statistics such as these can be found at (www.retrosheet.org).

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