

UDC 531.55:004.94

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SHOOTING ON THE MOVE: HOW MUCH AIM A ROBOT LOSES BY IGNORING ITS OWN VELOCITY, AND WHETHER A VIRTUAL-TARGET CORRECTION RECOVERS IT

Abstract: A robot that launches a projectile while driving inherits its own velocity, so a firing solution computed for a stationary machine misses. Competitive robotics teams handle this with a virtual-target correction, aiming at a shifted point rather than at the goal, but the size of the error being corrected, and whether the correction survives aerodynamic drag, are rarely quantified. This study builds a point-mass trajectory model of a FIRST Tech Challenge DECODE launcher with quadratic drag and evaluates it over the competition's own launch zones, 0.86 to 3.90 metres, using a real robot's measured flywheel calibration, hood range and top speed. Three results follow. First, drag alone is not a detail: a firing solution computed without it falls short by 0.27 metres at 1.75 metres and by 0.85 metres at 3.90 metres, that is 15 to 22 per cent of the range. Second, ignoring the robot's own motion costs roughly half a metre of range per metre per second of robot speed, reaching 1.48 metres at the machine's top speed of 2.73 metres per second, which is more than twice the width of the goal opening. Third, the virtual-target correction works: aiming at a point 0.5 to 1.5 metres nearer than the goal brings the residual error to within four millimetres at every range where a solution exists. The correction has one boundary, and it is geometric rather than aerodynamic: with a turret 0.30 metres above the floor and a hood limited to 60 degrees, targets closer than about 1.5 metres cannot be entered from above at all, moving or stationary, and raising the turret to 0.60 metres removes the restriction. The practical ranking for a team is therefore drag first, own velocity second, and flywheel-speed error a distant third, since a 5 per cent speed error costs 0.22 to 0.36 metres, less than driving at one metre per second and ignoring it.

Keywords: projectile motion; aerodynamic drag; robotics; FIRST Tech Challenge; trajectory simulation; shooting on the move

Introduction

During the DECODE season, my team FoxSlide initially relied on hardcoding three specific points on the field where we could shoot while staying still. We quickly realized this restricted our gameplay and cost us valuable cycle time, so we set a new goal: to shoot accurately from anywhere on the map, even while on the move. However, firing in motion caused our shots to consistently overshoot the goal due to the robot's forward momentum. Because our brute-force approach of relying on a few inflexible, predetermined shooting spots could not keep up with the constant, unpredictable movement of teleop matches, we knew we needed a dynamic solution. I began researching projectile motion and vector addition, which led me to the concept of a virtual target. By multiplying the robot's current velocity by the ball's estimated flight time, we could calculate a shifted aim point backward on the fly, allowing the robot's momentum to carry the shot into the real goal.

A robot that throws something while driving faces a problem that a stationary one does not. The projectile leaves the launcher with the launcher's velocity added to its own, so a firing

solution computed as if the machine stood still sends the ball past the target in the direction of travel. In competitive robotics this is called shooting on the move, and the standard answer is a virtual target: instead of aiming at the goal, the robot aims at a point shifted against its direction of motion, so that the sum of the two velocities carries the projectile to the real goal.

The logic is simple, and it is usually implemented from the textbook projectile equations, in which a body follows a parabola under gravity alone. Two things about that are worth checking rather than assuming. The first is whether the parabola is good enough. A competition ball is light and large, so the ratio of aerodynamic force to weight is not negligible the way it is for a dense projectile; if drag matters, then a correction derived from the drag-free equations corrects one error while leaving another in place. The second is how large the uncorrected error actually is. Teams treat shooting on the move as an advanced feature, worth engineering effort; whether it is worth more or less than, say, tightening the tolerance on flywheel speed is an empirical question that can be answered before any code is written.

This study answers both for a concrete, fully specified machine: the FIRST Tech Challenge DECODE field, whose geometry is published in the game manual, and a real competing robot whose flywheel calibration, hood range and top speed were measured by its own team during the 2026 season. The questions are: how much range does a firing solution lose if aerodynamic drag is omitted; how much does it lose if the robot's own velocity is ignored; does the virtual-target correction remove the second error once the first is modelled; and how do both compare with the error from an imperfect flywheel.

Materials and Methods

The machine and the field. The projectile is the DECODE artifact, a moulded polypropylene ball which the game manual specifies as "5 in. (12.70 cm) nominal" and "4.9 in +/- 0.25 in. (12.45 cm +/- 0.65 cm) in diameter at the mold seam"; the mid-specification value of 0.1245 m is used. The target is the goal, whose "top lip ... is 38.75 in. (98.45 cm) from the surface of the TILE", with an opening "26.5 in. (67.30 cm) wide and 18.3 in. (46.45 cm) deep". Shots are taken from two zones which the team measured on the field: a close zone from 0.86 to 2.50 m and a far zone from 2.50 to 3.90 m.

The launcher. The robot's flywheel was calibrated in-season by its team, giving five measured points from 1050 rpm at an exit speed of 3.76 m/s to 1700 rpm at 6.04 m/s. A least-squares line through those five points is $v = 0.003679 \cdot \text{RPM} - 0.296$ (m/s), which reproduces the team's own working relation to three decimal places. The simulation uses that line over a flywheel range of 600 to 2400 rpm, that is exit speeds of 1.91 to 8.53 m/s; the portion above 1700 rpm is an extrapolation of the team's own calibration and is identified as such. The hood adjusts the launch angle between 30 and 60 degrees. The launch point is taken to be 0.30 m above the tile; the manual does not fix this, so it is an assumption, and its consequences are tested directly in the sensitivity analysis. The robot's measured top speed is 2.73 m/s.

The mass. The manual gives the artifact's size but not its mass. For a hollow polypropylene ball of this diameter with a wall of the order of 1.5 mm, the mass is about 0.049 kg, and that value is used. Because it is an estimate rather than a measurement, the whole analysis is repeated at 0.040, 0.060 and 0.080 kg, and the result is reported.

The model. The ball is treated as a point mass under gravity and quadratic aerodynamic drag, with drag coefficient 0.47 for a smooth sphere and air density 1.225 kg/m³. The equations are integrated explicitly with a 2 ms step, and a shot is scored where the trajectory crosses the plane of the goal lip while descending. A shot counts as made only if its apex clears the lip by at least 0.25 m, since a ball arriving at the rim almost horizontally grazes it rather than dropping

into a 0.46 m deep opening. Spin is not modelled: a flywheel imparts backspin and therefore lift, which would extend the range slightly, so the drag-only model is a conservative bound in that direction, and the omission is stated rather than hidden.

The firing solution. For a given target distance, the hood angle is searched over its full range in one-degree steps and the exit speed is found by bisection for each angle. Among the solutions that land on the target with the required clearance, the one closest to 45 degrees is selected, that being the standard compromise between flight time and margin. The same procedure with drag switched off gives the textbook solution, and firing the textbook solution through the drag model gives the range lost to drag.

Shooting on the move. With the stationary solution fixed, the robot's velocity is added to the horizontal component and the shot re-flown, giving the uncompensated error, at robot speeds of 0.5, 1.0, 1.5, 2.0 and 2.73 m/s. The virtual-target correction is then applied: the aim distance is adjusted iteratively until the moving shot lands on the real target, and the residual error and the required aim point are recorded.

Reproducibility. The simulation is a single Python file using only the standard library; it and its full numerical output are released with this paper, so any number below can be regenerated.

Results

Drag is not a correction, it is the dominant term at long range. A firing solution computed from the drag-free equations and then flown through the air falls short in every case, and the shortfall grows with distance: 0.271 m at a target 1.75 m away, 0.457 m at 2.50 m and 0.851 m at 3.90 m. In relative terms that is 15 per cent of the range at the short end and 22 per cent at the long end. A ball that light loses a fifth of its reach to the air, so a team that programs the parabola alone will find its far-zone shots landing consistently in front of the goal and will, in practice, calibrate the difference away by hand.

Table 1 – Stationary firing solutions with drag, and the range lost by a solution computed without it.

Target distance, m	Hood angle, °	Exit speed, m/s	Flywheel, rpm	Flight time, s	Shortfall if drag is ignored, m
1.75	57	5.34	1,532	0.66	0.271
2.25	50	5.89	1,683	0.66	0.390
2.50	47	6.21	1,767	0.66	0.457
3.00	45	6.76	1,918	0.71	0.596
3.50	45	7.27	2,055	0.79	0.730
3.90	45	7.67	2,166	0.85	0.851

Ignoring the robot's own velocity costs about half a metre per metre per second. With the stationary solution unchanged and the robot driving toward the goal, the ball overshoots by an amount almost exactly proportional to the robot's speed: at a 2.50 m target, 0.252 m at 0.5 m/s, 0.496 m at 1.0, 0.730 m at 1.5, 0.957 m at 2.0 and 1.274 m at the top speed of 2.73 m/s. The proportionality is what the physics predicts, since the extra distance is the robot's speed multiplied by the flight time, and the flight time here is about 0.66 s. The size is what matters for a team: the goal opening is 0.673 m wide, so driving at a single metre per second and not accounting for it already puts the ball outside the opening, and at top speed the miss is more than twice the opening's width.

Table 2 – Range error from ignoring the robot's own velocity (positive is an overshoot), and the residual once the virtual-target correction is applied. The aim point is where the robot must point instead of at the goal.

Target distance, m	0.5 m/s	1.0 m/s	1.5 m/s	2.0 m/s	2.73 m/s	Residual after correction, m	Aim point at 1.0 m/s, m
1.75	+0.271	+0.533	+0.786	+1.029	+1.369	no solution	—
2.25	+0.258	+0.507	+0.748	+0.979	+1.303	+0.002	1.76
2.50	+0.252	+0.496	+0.730	+0.957	+1.274	+0.003	2.01
3.00	+0.263	+0.516	+0.761	+0.997	+1.328	+0.003	2.49
3.50	+0.281	+0.552	+0.815	+1.068	+1.423	+0.001	2.96
3.90	+0.293	+0.576	+0.849	+1.113	+1.483	+0.002	3.33

The correction works, and it works to within millimetres. Applying the virtual-target correction brings the residual error to at most 3 mm at every distance and every speed at which a solution exists, including the top speed of 2.73 m/s at the far end of the field. The correction is large: at 1.0 m/s the robot must aim roughly half a metre short of the goal, and at 2.73 m/s roughly one and a half metres short. In other words, the error is worth correcting and the standard correction is sufficient; nothing more elaborate is required once drag is inside the model rather than outside it.

The correction has a boundary, and it is geometric. At the closest targets the correction has nowhere to go. At 1.75 m the compensated solution does not exist: aiming nearer than that requires a trajectory the hood cannot produce. The same restriction removes the two shortest distances, 0.90 m and 1.25 m, from the table entirely, and it is not caused by drag or by motion. With a turret 0.30 m above the floor and a maximum hood angle of 60 degrees, a ball aimed at a target 1.25 m away reaches its apex at 0.99 m, within a centimetre of the goal lip, so it arrives at the rim flat instead of dropping in. Geometrically, raising the launch point fixes it: at 0.60 m the 1.25 m target becomes reachable with the required clearance, and at 0.75 m it becomes comfortable. Whether that is available to a team is a separate question, and for this competition the answer is no. Rule R105 caps vertical expansion at 0.457 m (18 in.) in normal play, which a 0.60 m launch point already exceeds. The manual does allow expansion to 0.965 m (38 in.), but rule G415 permits it only during the final 20 seconds of a match and only outside the LAUNCH ZONES, which is precisely where short-range shots are taken. The exception therefore exists and is closed exactly where this problem lives. The near zone is a permanent blind spot to be driven around rather than a defect to be engineered out.

Table 3 – Firing solutions as a function of turret height. A dash means no solution clears the goal lip by the required margin anywhere in the 30–60° hood range.

Launch height, m	0.90 m	1.25 m	1.75 m	2.50 m	3.90 m
0.30	—	—	57°, 5.34 m/s	47°, 6.21 m/s	45°, 7.67 m/s
0.45	—	—	54°, 5.11 m/s	45°, 6.02 m/s	45°, 7.50 m/s
0.60	—	58°, 4.30 m/s	49°, 4.89 m/s	45°, 5.80 m/s	45°, 7.33 m/s
0.75	—	53°, 4.01 m/s	45°, 4.69 m/s	45°, 5.60 m/s	45°, 7.18 m/s

Sensitivities. The artifact mass is an estimate, so the central result was recomputed across 40, 49, 60 and 80 g: at a 2.50 m target with the robot at 1.5 m/s, the uncompensated error moves from 0.691 m to 0.829 m across that whole range. The ordering and the practical conclusion are

unchanged; a heavier ball is simply less affected by the air, which also slightly increases the motion error because the flight is faster. Flywheel-speed error was tested at ± 5 per cent: it costs 0.223 to 0.227 m at 1.75 m, 0.305 to 0.313 m at 2.50 m and 0.358 to 0.360 m at 3.50 m. That is the comparison a team can act on. A five per cent speed error is worth about 0.3 m; driving at 1 m/s without compensating is worth about 0.5 m; driving at top speed without compensating is worth about 1.3 m.

Discussion

Three numbers summarise the result, and they come in a definite order. Aerodynamic drag costs a fifth of the range at the far end of this field and must be in the model before anything else is discussed. The robot's own velocity costs about half a metre for every metre per second of speed, which exceeds the width of the target opening at one metre per second. Flywheel-speed error, at a realistic five per cent, costs about a third of a metre. A team deciding where to spend its engineering effort should therefore model the air first, implement shooting-on-the-move second, and tighten flywheel control third, and this ordering is the practical contribution of the paper.

The virtual-target correction itself needs no defence: with drag inside the model it lands the ball within three millimetres at every distance and speed where a firing solution exists. What does deserve attention is where it stops working, because the reason is instructive. The failure at short range is not aerodynamic and not about motion; it is the geometry of a low turret firing into a raised opening. A ball launched from 0.30 m at a target 1.25 m away reaches the top of its arc at the height of the goal lip, so it skims the rim rather than entering, and no amount of correction changes that. Raising the launch point by a third of a metre would remove the restriction geometrically, but the competition's own size rules do not allow it. R105 caps vertical expansion at 0.457 m in normal play, below the height the geometry demands, and the one route above it, to 0.965 m, is gated by G415 to the last 20 seconds of a match and to positions outside the LAUNCH ZONES, which excludes the short-range case entirely. The practical conclusion is therefore the opposite of a build instruction. The short-range zone cannot be fixed by software correction or by physical extension, so it is a fixed property of the game for any robot of this architecture, and the usable response is a driving decision: treat the near zone as unshootable and position outside it. This is the kind of thing a simulation can establish before a season of trial and error spends matches discovering it.

Three limits bound these results. Backspin is not modelled, and a flywheel launcher always imparts it; the resulting lift lengthens the flight, so the true ranges are somewhat longer than the model gives and the drag shortfall in Table 1 is an upper bound. The artifact mass is estimated rather than measured, although the sensitivity analysis shows the conclusions hold across a doubling of it. And the model is two-dimensional: it treats the robot as driving directly toward the goal, whereas a real robot moves at an angle, which introduces a lateral component this design does not address. The natural next step is a wind-tunnel-free measurement of the ball's actual drag by filming a few shots and fitting the trajectory, which would replace two of these assumptions with data from the field itself.

While I expected the robot's momentum to significantly overshoot our targets, I was surprised to find that aerodynamic drag was actually our largest source of error, costing up to 22 per cent of our range. It was also unexpected to learn that our close-range misses were a strict geometric limitation caused by our 0.30 m turret height. Knowing this, I would immediately integrate a drag-compensation model into our firing code rather than focusing primarily on the robot's velocity. Most importantly, because the DECODE manual caps vertical expansion at 18

in. in normal play and only lifts that cap outside the launch zones in the last 20 seconds, raising the turret to 0.60 m is not something we are allowed to do where the short shots happen, meaning close-range shots are a permanent blind spot that our drive team must strategically avoid, since neither software corrections nor physical extensions can fix them.

Conclusion

For a FIRST Tech Challenge DECODE launcher operating over the competition's own launch zones of 0.86 to 3.90 m, a firing solution that omits aerodynamic drag falls short by 0.27 m at 1.75 m and by 0.85 m at 3.90 m, 15 to 22 per cent of the range. Ignoring the robot's own velocity produces an overshoot proportional to that velocity, 0.50 m at 1 m/s and 1.27 m at the measured top speed of 2.73 m/s at a 2.50 m target, which exceeds the 0.673 m width of the goal opening at every speed above about one metre per second. The virtual-target correction removes this error to within 3 mm at all distances and speeds where a solution exists, and it requires aiming 0.5 m short at 1 m/s and about 1.5 m short at top speed. The correction fails only at the closest targets, and for a geometric reason: from a turret 0.30 m above the floor with a hood limited to 60 degrees, targets nearer than about 1.5 m cannot be entered from above at all, while a turret at 0.60 m removes the restriction. Ranked by what they cost, the three error sources are drag, then own velocity, then flywheel-speed error at about 0.3 m for a 5 per cent deviation.

Acknowledgments

Field and projectile specifications are published by FIRST in the 2026 FTC DECODE game manual and are freely available. The flywheel calibration, hood range, launch-zone measurements and robot top speed were measured by FTC team FoxSlide #29029 during the 2026 season. The simulation code and full numerical output are released with this paper. The author declares no conflict of interest and received no funding for this work.

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