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# Boom Motion and Spray Coverage

## Introduction

Uniform and efficient spraying remains one of the most critical challenges in modern crop production. The importance of boom stability has increased with the rapid growth of high-capacity self-propelled sprayers. These modern machines often operate at speeds up to 15 to 18 mph and are equipped with booms extending up to 135 feet that cover a great number of acres per hour. However, application rate and coverage accuracy depend on a simple assumption: **each nozzle moves at the intended speed and stays near the optimum intended height above the crop canopy.** In real field scenarios, these assumptions often fail because the boom is a long, flexible structure that moves in response to terrain, acceleration, braking, steering corrections, and machine dynamics. Boom motion causes changes in nozzle position relative to the crop canopy and alters nozzle travel speed relative to vehicle. These localized changes lead to visible spray application errors in the field (Ooms et al., 2003), even when the sprayer monitor indicates that the correct application rate is being delivered.

Boom stability is a critical indicator for coverage quality because it affects **where the droplets** and the amount of **product from each nozzle land** during field operation. These boom motions (both fore-aft and up-down) can create:

*Figure 1. Types of boom motion: (Δx) Horizontal motion and (Δz) Vertical motion.*

- **Under-application** (reduced weed or pest control),
- **Over-application** (crop stress and wasted chemicals),
- **Higher drift risk** (especially when parts of the boom run too high), and
- **Canopy strikes and component damage** (when parts of the boom run too low).

Boom motion can also create impacts beyond coverage. Drift from a boom running too high can move spray off-target toward field edges, waterways, or nearby sensitive crops, increasing environmental and complaint risk. At the same time, uneven application can lead to re-sprays and wasted product, adding cost in chemicals, fuel, and time.

## Limitations with Current Technology

- *Pulse Width Modulation (PWM):* Pulse Width Modulation (PWM) controls flow by rapidly switching each nozzle on and off and adjusting the **duty cycle**. These systems also use sprayer turning information (for example, **yaw/turn rate**) to do **turn compensation**, so nozzle flow rate is based on individual nozzle speed (inside nozzles apply less and outside nozzles apply more) during a turn. This helps correct flow rate differences caused by turning, minimizing off-rate errors. However, control system ascertain the nozzle speed primarily based on vehicle motion and yaw/turn rate provided by inertial sensors mounted on the sprayer chassis. Prior research has shown that system may not know the true, instantaneous speed of each nozzle caused by **boom surge** (forward–back tip motion) during normal field travel. In the absence of this knowledge, the control system cannot accurately implement duty cycle and would potentially result in misapplication bands created by boom motion (Sharda et al., 2016; Singh et al., 2025; Kaloya, 2025)

- *Automatic boom height control (ABHC):* Boom height control systems aim to maintain a target height above the ground or canopy and can improve **average boom height**, but field performance is still limited by **sensor spot measurements** and **system response time** — especially in rough or across-slope conditions. As a result, some boom oscillations remain, and the boom can still spend a significant amount of time away from the targeted spraying height, as can be seen in the field data shown in Fig. 3 (Sharda et al., 2016).

While the current technology can sense the vertical boom motions to some extent, it does not have the capability to capture horizontal motions. The absence of this information leaves the users with limited knowledge on individual sprayer boom motions, both horizontal and vertical, driving considerations and sprayer boom selection for optimal product application and coverage.

## Computer Vision System for Real-time Boom Motion Quantification

In recent work within the FarmsLab, a computer vision (CV) Distance Quantifier System was developed to measure sprayer boom motion in real time (Dalal et al., 2026). Using a single calibrated camera, integrated with a Global Navigation Satellite System (*GNSS)* receiver and ABHC radar sensors, the system tracks the boom and estimates movement in both the fore–aft and up–down directions. When tested against ground-truth measurements, it measured boom displacement with an average error of less than 1 inch. This capability makes it possible to quantify how often the boom is too high, too low, or surging (speed), and it could be used in the future as feedback for improved boom and spray control. This CV system was used to measure left boom-end motion during field experiments in Clay Center, Kansas (2025) at 6, 12, and 18 mph to evaluate how boom movement affects spray coverage (Kaloya, 2025).

## Boom Motion and How it Changes Spray Coverage

Boom motion relative to spraying vehicle is not just vibration. In practical field operations, every spraying nozzle on the boom has two “inputs” that drive coverage.

- Nozzle speed over the ground (mainly affected by Horizontal Boom Motion (fore-aft))
- Nozzle height above the target (mainly affected by Vertical Motion (up-down)),

Which, as a coupled mechanism, affects the spray coverage and uniformity.

*a). Horizontal Motion (fore-aft):*

Most sprayers regulate application rate based on the machine’s forward travel speed, with some systems accounting for turning or yaw through pulse-width

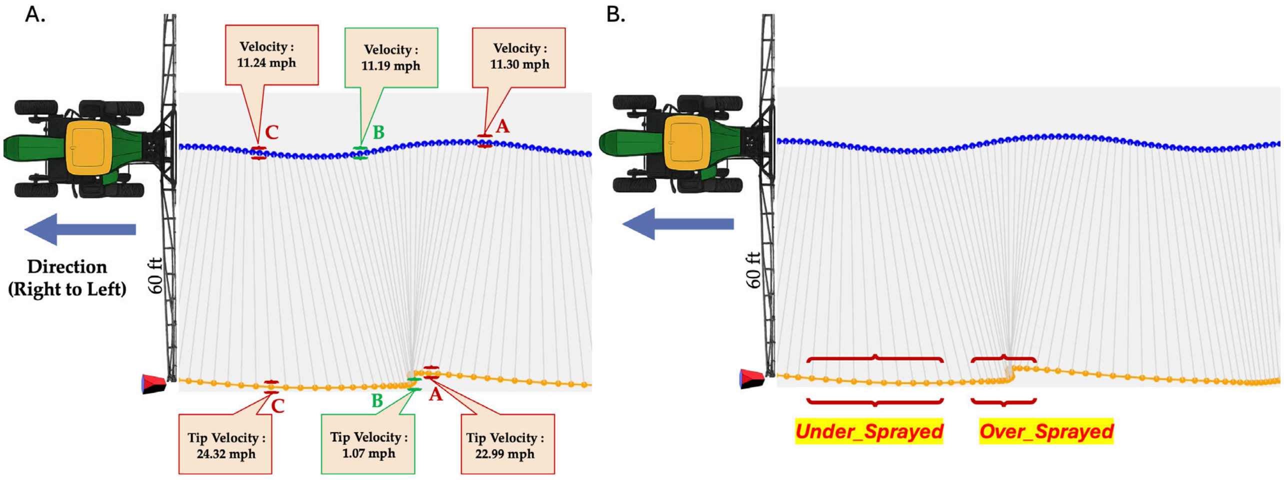

*Figure 2: Example of horizontal boom surge measured in the field. Blue line shows the GNSS track at the boom center; orange line shows the left boom tip path measured. The sprayer image is illustrative. Forward surges increased nozzle ground speed, creating under-spray, while backward lags decreased speed and caused over-application. Direction of sprayer: Right to Left.*

modulation (PWM) control (Luck et al., 2011). However, the boom tips can surge forward or lag backward due to acceleration, braking, terrain transitions, and chassis pitch. That means true nozzle ground speed is not always equal to vehicle speed, especially near the boom. Such effects of horizontal boom motion and rapid nozzle or boom-section on/off actuation on nozzle flow dynamics and application accuracy remain poorly understood.

True nozzle speed = vehicle speed ± boom surge speed.

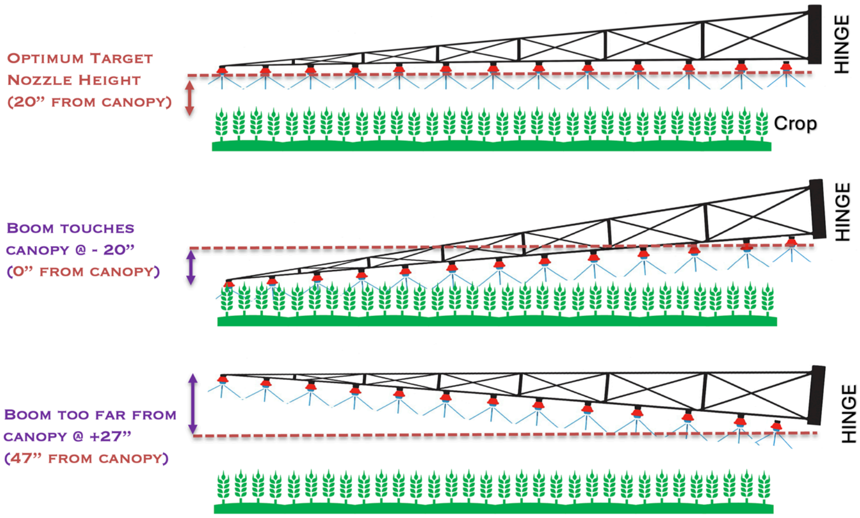

*Figure 3: Illustration of how boom behaves in the vertical direction in field.*

If nozzle ground speed increases but flow is still based on vehicle speed, the sprayer applies less per unit area (underapplied), and if the nozzle ground speed decreases, the sprayer applies more per unit area (over-applied). Data collected from a large self-propelled sprayer during field operation shows an example scenario of a sprayer in a zigzag motion (Fig. 2). This maneuver depicts machine states that represent a boom forward surge leading to under-spray, and a backward lag leading to over-application. The analyzed data from CV system exhibited that the point (A), (B) & (C) on the Sprayer path (Blue) showed consistent speed of 11.5 mph, whereas the corresponding reference points on the Boom Tip Path (Yellow) (A) showed increased speed of 23.0 mph, 1.1 mph speed at point B because of the backward motion and again increased to 24.3 mph at point C. The boom speed variations would cause over-sprayed and under-sprayed zones in the run. These results showed that during real-world sprayer maneuvers horizontal boom moves extensively creating application rate error scenarios, and knowledge of extent of such scenarios can help operators to avoid such machine states while minimizing application rate errors. Manufacturers could also use this information to adjust each nozzle's flow based on its true ground speed, improving application accuracy.

For the Horizontal motion, using the 10% rate-error threshold around the target rate (Sharda et al., 2011), the sprayer boom of the commercial sprayer used in 2025 Kansas field experiments, exceeded that level about 1.0% of the time/boom-area at 6 mph, and almost ~ 2.0% at 18 mph on a 14 acre. In simple terms, only about 1–2% of the run had horizontal surge events large enough to create noticeable under- or over-application bands at the 10% level (Kaloya, 2025).

Even though ~ 2.0% may sound small, it still matters in a 100-acre field, 2.0% is roughly 2.0 acres, and in a 1,000-acre season, it is roughly 20 acres where the sprayer could be more than ±10% off-rate during surge events, showing a real agronomic and economic impact (Kaloya, 2025).

### *b). Vertical Motion (up-down):*

Sprayer in-field operation also induces vertical boom disturbances causing variations in the nozzle to canopy height. Most field recommendations for **110° flat-fan nozzles** place the boom near **20 inches (about 0.50 m)** above the canopy. This height helps maintain the intended spray pattern overlap and improves uniform coverage (Kruger, 2019; Zhao et al., 2022). The farther the boom is above the target height, the higher is the risk of drift (Pan et al, 2025). Even small deviations in nozzle height can cause uneven deposition by altering droplet velocity and impact energy (Nuyttens et al., 2009; Holterman, 2003). If the boom is too high, droplets travel farther and are more likely to drift away; if the boom is too low, the spray fans and overlap significantly deteriorates, causing wet streaks under the nozzles and lighter coverage between them. Figure 3 illustrates the possible errors in spray distribution resulting from the up-and-down motion of the sprayer boom. Figure 4 shows an XY scatterplot of vertical boom quantified during the same field experiment using

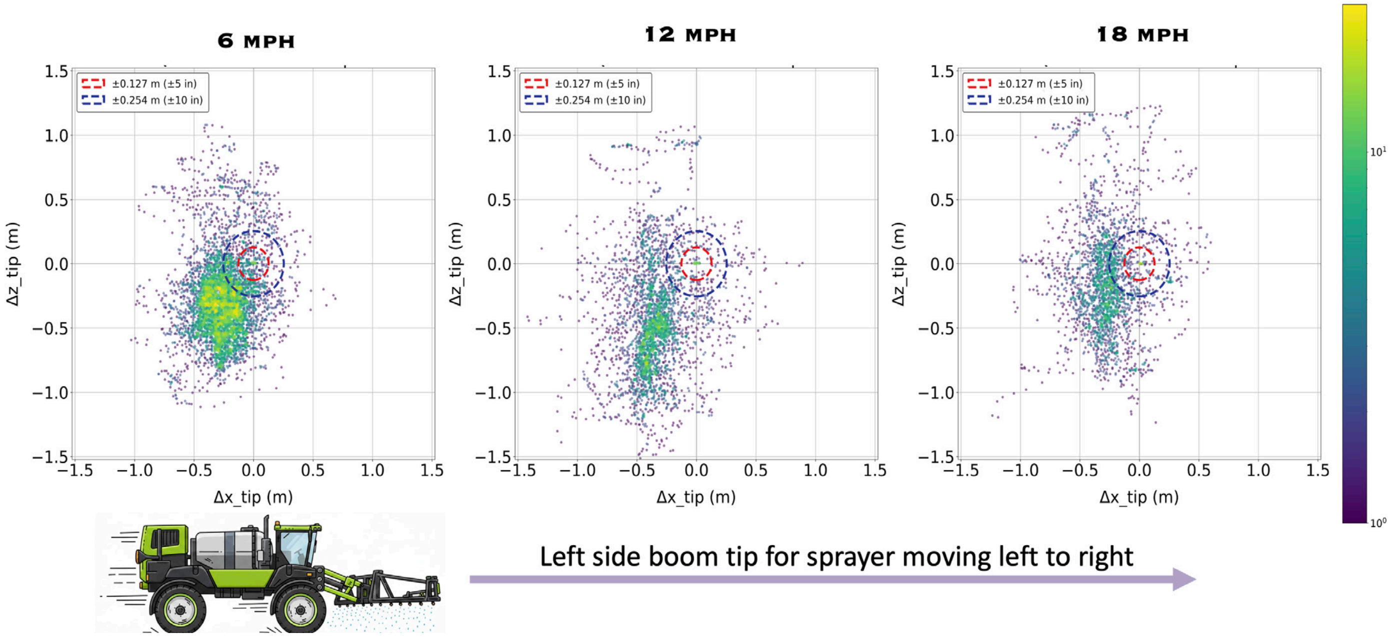

*Figure 4: XY scatterplots of (DQS) horizontal vs vertical displacement (Δx vs Δz) for sprayer running at 6, 12, and 18 mph. Dashed circles in Red represent boom motion within ±5," and dotted circles in Blue represent boom motion within ±10": the crosshairs = stabilized (0,0) at the start, and the dot color indicates relative sample density (log scale).*

CV system. Each point in the scatter plot represents the position of the left boom end in a fixed reference frame with regard to the target starting location point in the center. The dashed circles in the red represents a ±5 inches (boom motion) and in blue, ±10 inches of boom motion (blue) reference tolerance bands around the initial stabilized (0, 0) target position.

A large part of Vertical Motion behaves like the boom is **pitching (rotating) about the hinge (where the boom can be adjusted forward/backward & up/down)**. A clean way to summarize that motion is the **tilt angle (θ),** computed from the tip displacement and boom length. In the real field operation experiment conducted in 2025, the results indicated that the boom usually tilted between 1 to 2°, but during the larger motion events tilt angle could be 3.5 to 4.5° (Kaloya, 2025).

If we consider **±10 in** vertical boom travel (±10 inches above or below the target boom height) as acceptable tolerance limit for the vertical motion, the data indicated that the **boom end section's vertical travel increased with travel speed**. The boom end height was beyond **±10 inches** for about **20%** of the time at **6 mph** and nearly doubled to about **40%** at **18 mph** (Kaloya, 2025). This system can be potentially integrated with the current technology to either 1) automatically shut-off nozzle control section which are beyond certain vertical height thresholds to reduce excessive product loss or, 2) automatically control boom motion and/or controls vehicle speed to realize boom vertical travel within acceptable zones.

## Future Technology Features Considerations

- The CV Distance Quantifier System can quantify both vertical (up-down) and horizontal (fore-aft) boom displacement continuously during real-world operating conditions, and it can show how often the respective spray nozzle is outside desirable "good spraying" ranges. For example, this system can tell an operator:
  - Percent time each nozzle was beyond ±10 inches of target height on a spatial scale.
  - Horizontal boom surges (mph) and percent time boom surges create application rate errors beyond ±10%.
- **Real-time spray application control**: As we can calculate the actual speed of the nozzle with respect to the sprayer with the CV (Distance Quantifier System) system, this data can potentially be used by the control system to generate accurate duty cycles at each nozzle to implement target nozzle flow rates in real time (Kaloya, 2025).
- **Section control during "do not spray" height events (Potential New Functionality).** If a system can detect when the boom is **too high**

(higher drift risk) or **too low** (canopy contact risk), it can support simple "do not spray" logic (temporary shutoff) during those periods to minimize drift risk and banding of chemical.

## Field-practical Suggestions for Operators

- Manage speed in rough zones: Boom motions when accelerating and braking (approaching terraces and headland) can be minimized by slowing down to reduce both vertical height errors and horizontal surge errors.
- Avoid abrupt acceleration and braking: Smooth inputs reduce boom surging and pitching events.
- Set boom height carefully: Follow the height guidelines specified for the nozzle manufacturers for sprayers being used and often check settings in the field.

## Conclusion

Boom motion affects spray coverage by changing the nozzle's ground speed (horizontal surge) and the nozzle-to-canopy height (vertical motion). Field measurements showed that percent time nozzles are beyond an acceptable height threshold ((±10 inches) increased with speed. Such instances when the nozzle height are outside acceptable levels would create high-risk and low-value application zones. Similarly, the horizontal surge can create under- and over-application bands that may affect a meaningful acreage over the course of a season. Together, these observations exhibit that boom motions impacting spray coverage deterioration occur more frequently and operators needs to be mindful of technology they own to minimize such instances by correctly setting up sprayers and also manage driving styles to realize optimal application efficiency, product performance, and drift reduction.

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