# IMPROVED PATHS FOR UAVS IN PESTICIDE SPRAYING WITH TERRAIN CONSIDERATION

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### *ABSTRACT*

*This research was designed to investigate the use of unmanned aerial vehicles (UAV) in the agricultural industry. The application of pesticides on farmland by traditional methods such as spraying has several disadvantages including dangers of exposure for farm personnel, uneven application results and a greater rate of spray contaminating regions beyond the target area. UAVs potentially could improve the pesticide application process depending on the flight leg paths that attempt to maximize the weighted (by terrain area) cumulative sum of applications over segments of the application flights.*

### *KEYWORDS*

*UAV, Pesticide Spraying, A* Algorithm.*

## 1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have been adopted by agricultural organizations for use in many applications [1]. Advances in guidance technologies enable many UAVs to execute complicated flight patterns autonomously [2]. Some of these missions involve flight pesticide application approaches, and a route can be planned in advance of the target field using geographically referenced waypoint coordinates that include latitude, longitude, and true altitude. The UAV can then fly the assigned route free from outside influences. Recent research has strived to find more efficient and effective route-planning methods for UAVs [3]. More efficient routes have been shown to reduce the amount of pesticide released into the environment by using Mixed Integer Linear Programming (MILP) [4], the A* algorithm [5], Evolutionary Algorithms [6-7] and several other techniques, such as in Heinze & Karim [8].

Efficient route planning normally involves finding the specific conditions that promote optimal pesticide application. In order to reach the established goals, such as having the UAV fly over fields [9], finding the shortest route in terms of time travelled [10], or conserving as much fuel as possible by taking advantage of prevailing winds [11]. The subject of the research description that follows is one of planning the most optimal routes in the use of sprayer-equipped UAV for pesticide application [12].

By following farmland contours, a sprayer-equipped UAV is continuously in a better position and orientation to observe the topography and terrain being sprayed. Figures 1 and 2 demonstrate how terrain effects spray coverage. UAVs that use a uniform distribution path will only spray consistently if the terrain is flat and there is no wind. This seldom is the case. The UAV's path should maximize the Probability of Accurate Application (POAA).

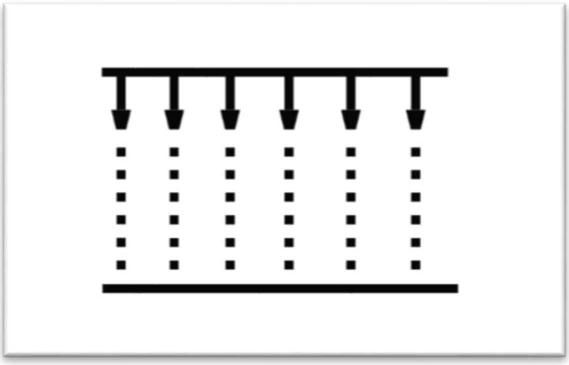

Figure 1. Pesticide spray coverage on flat terrain

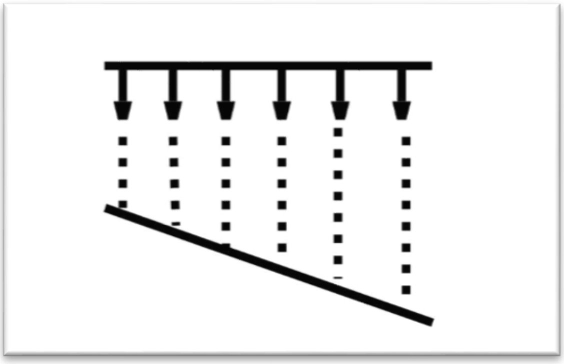

Figure 2. Pesticide spray coverage on uneven terrain

Modified UAV flight routes contrast with standard linear "parallel sweep" routes that are normally utilized by standard farm machinery. Standard linear patterns do not take into account variegated, non-uniform terrain. Parallel spray routes were considered exclusively in the performed research as opposed to spiral or other route types, as these are most commonly used in the case of uniform probability containment areas [13] that were evaluated in the study. There are also other reported datums, such as line and generalized datums, see Frost [14] for more information.

As a result, the lesser the distance of the sprayer to the crop, the higher the application rate of pesticide will be deposited onto the crops. If at any time along a parallel spray sweep, intervening terrain or other visual obstacles block a potential line-of-sight between the farmland and the UAV the application could be affected. Therefore, in order to maximize the cumulative sum of POAAs at various locations over the length of consecutive legs, an improved UAV spray path should attempt to reduce distance to the terrain being sprayed and also attempt to ameliorate the potential of intervening terrain and other objects to block visual variations in the terrain.

The hypothesis of the performed pesticide application was that straight lines do not improve the spray patterns, but paths that closely follow the various topographic hills, valleys, and folds of a terrain surface do. The path changes would be in order to more maximally exploit the usefulness of the UAV's spraying abilities at all times. This approach resulted in a higher probability of pesticide application success on a farm, as the straight-line technique. The issue being addressed by this research was to identify if the research hypothesis is true or false. Measurable results reflected in positive changes in POAA values.

## 2. RESEARCH GOALS

The performed research was to investigate potentially improved UAV Pesticide Spray leg paths that attempted to maximize the weighted (by terrain area) cumulative sum of POAAs over segments of intervening terrain on consecutive spray patterns. Maximized POAAs values resulted in an increase in the overall probability of success of coverage.

A comparison of spray leg path techniques was implemented using a stochastic Monte Carlo simulation environment (similar to the work of Ayani&Kamrani [15]) specifically created to determine the outcome of this research. The first technique investigated consisted of standard straight-line pesticide application leg paths at true and terrain-following flight paths. The second technique consisted of the previously described terrain-following spray patterns that factor in the elevation of the terrain and any potential visual obstacles.

If one or more variations of the second technique resulted in an improved summation of calculated weighted POAA over the terrain, and therefore a higher resulting POAA, for the same overall UAV pesticide application effort (which can also be considered flight time if traveling at uniform speeds), it can be concluded that this is a superior alternative to straight-line pesticide application leg paths for UAVs involved in agricultural practices. Findings can be conclusively demonstrated by repeated and statistically significant higher overall pesticide application success rates.

It can be analytically proven that improved POAA values can use pesticide application theory rather than actual flights. If it can be shown that summation of POAAs multiplied by terrain area segments over a total area of containment is increased over an alternative, POS will also increase in similar situations [16]. However, analysis shows that actual demonstrations are a better approach to investigating and maximizing the benefit of alternative pesticide application methods, since it is difficult or impossible to estimate the effects of changes in various path techniques using analytic equations [17].

## 3. APPLICATION

Waypoints are often used on projects using pre-planned UAV flight paths. The most used applications include military targeting [18], radar countermeasures [19], search and rescue [20, 32], aerial mapping [21], and reconnaissance missions [22]. The numbers of UAVs in usage are rapidly increasing, and this trend is likely to continue increasing [23]. This research related to UAV flight paths is likely to be instrumental in the development of additional applications in the future. The costs of utilizing UAVs for many tasks is lower than that for manned vehicles or aircraft. This has an additional benefit of keeping personnel safe [24]. Therefore, demonstration of a technique for improved pesticide application paths is likely to further reduce costs in the agricultural industry [25], improve application efficiency, and be utilized in practice in the field with an increasing adoption.

## 4. A BRIEF REVIEW OF LITERATURE

There is a substantial amount of recent research related to optimal pathfinding for UAVs used to spray pesticides. A number of these attempt to address problems with spraying pesticides.

Optimal path spraying must adjust for drift control [26] and weather [27] have been developed. Numerous artificial intelligence algorithms have been addressed including Particle Swarm Optimization [13] and Genetic Algorithms in [9] and [1].

## 5. RESEARCH METHODOLOGY

The spray approach followed for the performed research was similar to that described by Arévalo et al. [3-4] in their papers on UAVs in changing environments. This research utilizes the A* algorithm for route planning. However, instead of incorporating probability of traditional spray applications into the cost function of the A* algorithm to find an improved path, utility of the relative UAV camera position and orientation were used in the cost function to induce the UAV to fly through improved spray nozzle orientations. Improved spray positions and orientations are defined as those positions and orientations which increase overall POAA over uneven terrain area on pesticide application routes.

The Arévalo et al. approach to the spray application problem uses 3D path optimization in Euclidean space. Path variables include the UAV's state, and include position of the sprayer, speed, and orientation. Path constraints are derived from a model of the UAV flight characteristics, including minimum turning radius over fields, minimum and maximum flight speed factoring in winds, and maximum climb rate. The A* algorithm evaluation function uses cumulative distance from the path origin and a weighted value of the probability of spraying as a movement cost, and Euclidean distance to the agricultural target as the heuristic value. The radar model produces a probability of a more accurate spray pattern on a cross section value of the UAV. Euclidean 3D space is divided into an array of cells (with axes of x, y, and z as depicted in Figure 3), and a movement spray path is calculated through a series of cells. Cells can also include various obstacles, in which case movement though the cell is blocked. Possible spray movement between cells during path calculation is limited by the UAV flight elements model and variables. Pesticide risk in each cell is calculated during A* inter-cell movement evaluation, and the relative value is added (using a weighting factor) to the cumulative cost to reach that respective cell. As a result, the UAV movement over agricultural areas are guided to cells with relatively lower spray risks, while at the same time satisfying flying characteristic constraints, and also attempting a least-distance traveled path.

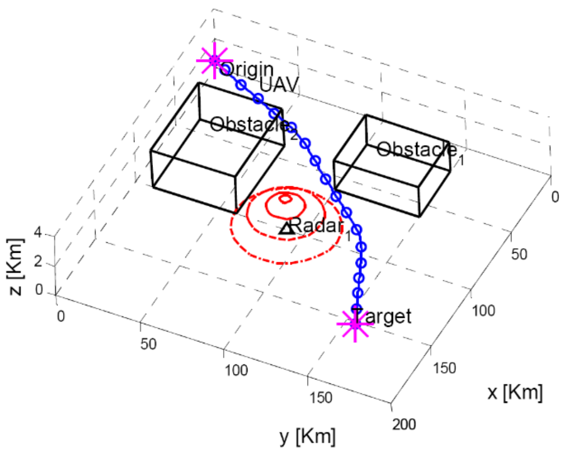


Figure 3. Pesticide spray coverage on uneven terrain

This research is described by Arévalo et al. in that a nearly identical example model of 3D Euclidean space is used, UAV flight characteristics and constraints are the model, and part of the model optimized path is computed using the A* algorithm, total distance is used as the movement cost, and Euclidean distance to a spraying leg end-point destination is used as the heuristic value. This research differs in the weighted additional cost added to the total movement cost evaluation. Instead of using an additional weighted cost based on the risk of pesticide applications, the weighted additional cost is based on the comparative value of the UAV's camera position, sprayorientation and for terrain application purposes. Favorable values result in lower costs. Also, the simulation date that was created will, similarly to the Arévalo et al. work, include terrain surface and sample elevation data based on publicly available data.

Figure 4 illustrates the geometry and various distance measurements related to a UAV-mounted pesticide sprayer. Point "O" is the location of the sprayer(s) of the UAV. In Figure 4 it is flying from right to left with a trail of pesticide behind it. Point "A" is the location on the terrain the UAV is spraying. The absolute altitude of the UAV above the surface (also known as "height-above-ground" (HAG) altitude [14] is demonstrated by length "h". The angular height of the sprayer field is shown by angle "α". The angular width of the sprayer field is shown by angle "β". The height and width of the terrain surface visible is indicated by lengths "a" and "b" respectively. The distance from the camera to the terrain covered by the sprayer is shown by length "s". The pesticide lands on the field behind the UAV as it travels the path.

Figure 4 is included so that there is a basis for the programmatic implementation of pesticide spray modeling in the simulation environment. As the UAV moves forward, the sprayer "footprint" formed by width "b" and height "a" also moves forward to contain new terrain areas that may be at various slopes and orientations relative to the orientation of the sprayer. If the UAV flight path rotates on the x, y, or z axis (or axes), there will be various changes in the location, shape and size of the rectangle formed. This change covers new terrain areas. This is the geometric mathematical model approach that was used for sprayer movement. The research has attempted to fully understand all the implications, both quantitative and qualitative, of pesticide sprayer movement. The model is able to be adjusted while considering all potential implications of various movements in sprayer effectiveness.

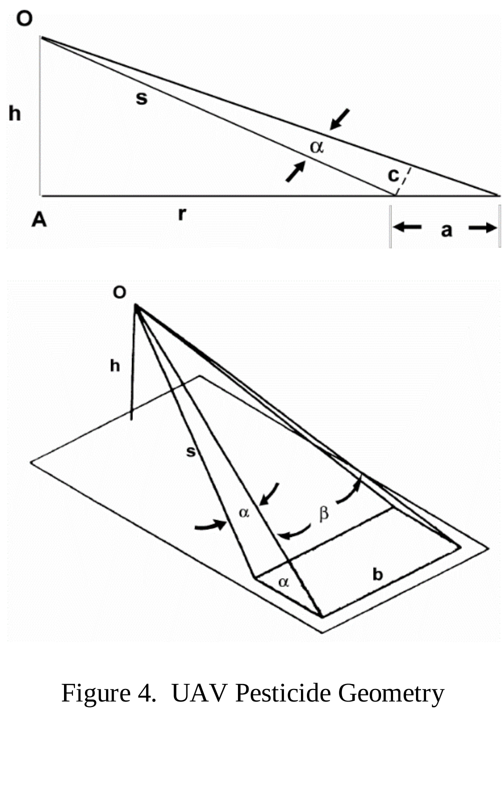


Figure 4. UAV Pesticide Geometry

This research uses the assumption that the application in the pesticide sprayer is an inverse cube as shown in Figure 5. Area directly in the path of the spray receives 100% coverage and coverage decreases moving out from that area due to wind and general disbursement. Other pesticides might have slightly different distribution equations based upon their characteristics like density and composition.

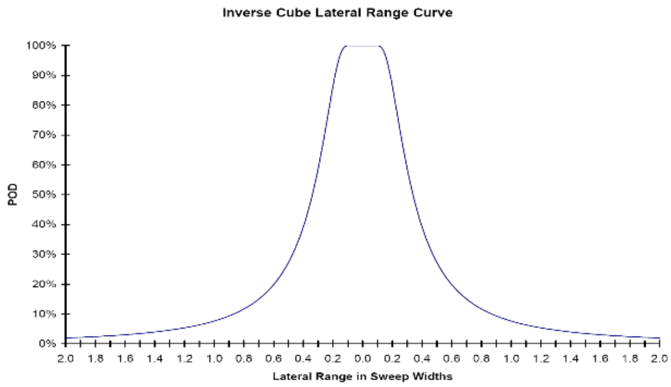


Figure 5. The Inverse Cube Lateral Range Curve Function

A metric was developed to calculate prospective utilization of the sprayer's position and orientation. This metric takes into account POAA of sections of the terrain area to be covered, and total elevation of the terrain area.

The sprayer application for purposes of simulation consisted of the following:

1. A uniform pesticide spray probability density distribution in the target area.
2. An inverse cube visual pesticide coverage function model.
3. The agricultural field is passive and non-moving.
4. Pesticide spraying does not guarantee complete coverage.

The test environmental terrain model consists of grid-squares divided at one-hundred-meter intervals. However, the model can be adjusted for other intervals base upon factors such as type of UAV, type of pesticide and environmental factors. Terrain elevation data is tailored to the grid-square vertices. Satellite orthoimage photos are then superimposed on terrain areas, and a map grid-square database is partnered with ground terrain type and vertically protruding terrain coverage. Path movement cells have a length and width of one hundred meters above the agricultural surface, however the height of each cell is adjustable to allow consideration of various maximum UAV flight characteristics, climbs and descent rates.

In sum, the performed pesticide spray paths primarily attempt to minimize distances from the sprayer to the terrain and maximize the width and height of the terrain to the sprayer at all times. Resulting improvements are then able to be discovered through the pesticide application simulation.

## 6. BARRIERS AND ISSUES

The primary task completed by the research was the creation of a simulation environment to test the various existing and performed pesticide spray methods. Several foundational issues were addressed during the course of this agricultural research, where a variety of solutions, alternatives and explanations were identified for each result. A few are addressed in the following:

1. Spray operation during cross-leg traverses. It was assumed the UAV sprayer is not operational during cross-leg traverses to simplify the pesticide application simulation. The sprayer was only considered to be operational during actual pesticide spraying segments. The effect of this turned out to be immaterial, as not only is the sprayer at a perpendicular angle to the agricultural field, but application turn points will be outside the respective area of spray application. This is to ensure thorough coverage of the spray pattern area by the sprayer at both the start and end of each field location. Since spray angles tend to be set down from the UAV, this is an important consideration.

2. Establishing credible sweep width (W) values for various sensors (sprayers), at various distances and under various environmental weather conditions.

3. The issue of terrain coverage is considered. Natural and man-made terrain cover such as trees, woods, forests, jungle, low-grass, high grass, rocks, and buildings, will decrease overall POAA in agricultural areas in contrast to similar terrain with little or no vertically protruding terrain cover such as clear areas or areas with roadways. Likely values and effects, and specific POAA percentage degradation values for various agricultural terrain and crop cover types, are adequately documented.

4. The creation of a theoretically credible and practicable metric to determine the relative merit of sprayer position and orientation over terrain in relation to other positions and orientations. As an example of one possible approach, the projection of the pesticide sprayer can be transposed into a rectangular area onto the visible terrain (the rectangular area encompassed by length and width of "a" and "b" as shown in Figure 4). This agricultural area can be subdivided into regions by a factor of one hundred. POAAs in various regions which could then be calculated based on the distance to the sprayer from each sub-area region (which could then also be adjusted by a coefficient factor that considers agricultural cover, such as trees), and multiplied by the respective terrain area length and width to create a weighted value. Resulting sub-area values could then be summed to create an overall value of agricultural terrain area multiplied by adjusted region POAAs. There are many possible approaches and Ousingsawat [28] also offers some guidance in this regard in its results.

5. The issue of spraying the same terrain two or more times along a flight path. Pesticide spraying consistent with Bayes' Rule [29] indicates spraying the same terrain consecutive times will improve POAA for that area. Any sprayer pattern algorithm will have to consider this important fact. It was possible terrain previously sprayed would be marked and this was implemented in the A* prospective movement cost function using a weighting factor.

6. Neighboring agricultural path visibility. In certain areas along the sprayer’s path, the sprayer may be in an ideal position to cover terrain within a previous or subsequent spray path terrain boundary area. An approach to maximizing the benefit of this effect, while attempting to prevent or mitigate the effects of repeated terrain spray passes while on neighboring legs, was developed. This involved the flagging of individual terrain areas as having been previously sprayed.

7. Experimentation with the sprayer cost-weighting factors. The performed implementation of the A* involved in this study had as a primary goal the attempt to minimize the cost of spraying agricultural fields. An attempt to develop a heuristic or analytical approach to determining ideal weighting factors presenting the most likely pesticide application success under various conditions was made.

8. Confirming the benefit of, or offering an alternative to, theoretically optimal pesticide application. On terrain that can include areas with higher and lower overall POAAs (for example,

wooded or low vegetation areas will have much lower POAAs than clear terrain for aerial pesticide spraying), a heuristic or analytical approach can be shown to yield better results than theoretical approaches and improve likely coverage for POAA.

9. Evaluating the enhanced effects of high-quality sprayers. Many UAV sprayers are now equipped with additional mounts for cameras with zoom lenses. [30]. These features make it possible to improve relative sprayers and corresponding POAA values. It was possible to include in the path movement routines a further enhancement for optimizing pesticide sprayers and record the results at various pre-planned locations along the path.

## 7. RESOURCES USED

Elevation data from the Shuttle Radar Topography Mission (SRTM90) was used in building three-dimensional agricultural terrain models of areas likely to be included in pesticide applications. This information is available from the U. S. Geological Survey website for public usage. SRTM90 data can be found in geographically referenced terrain elevation cells nominally spaced at 90-meter intervals. This data can be incorporated into consistent 100-meter per side grid-squares or smaller squares if needed. The data is available for researchers and the general public including U. S. national parks and other rural areas often used in farming.

Satellite photo orthoimages are available and can be overlaid upon terrain elevation data grid-square areas in order to determine individual terrain cell's estimated terrain cover values. Several agricultural terrain models have been developed with various types of topography. The terrain models utilized were used with Monte Carlo simulation of UAV flight paths to derive comparative agricultural pesticide application results.

## 8. RESULTS AND CONCLUSIONS

The work of Arévalo et al. was duplicated and extended to the field of pesticide applications. Arévalo et al. devised an approach using the A* algorithm to route UAVs over fields while attempting to avoid common sprayer difficulties. The performed research uses the same approach; however, it substitutes into the cost function of movement UAV pesticide spray positional utility instead of radar detection probability. In the performed modifications, more advantageous spray positions have lower movement costs attached to them [31].

It has been shown the result of this technique is improved UAV pesticide spray applications over agricultural terrain, which will be in contrast to standard straight line pesticide applications at fixed absolute or true altitudes. Various strategies for pesticide applications (including standard and modified versions) are compared using simulation and the results documented. Search improvement noted from the simulation results show increased POAA from identical spraying efforts. Similar work was performed by Pelosi et al [32] on the problem of search and rescue using UAVs.

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