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Evaluation of a Spray Scheduling System ⋆

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Abstract:
There are many applications for outdoor automation in agriculture and horticulture that require liquid to be sprayed variably across a linear boom while a robotic vehicle moves the boom across a field or orchard. This paper examines the modification of an existing scheduling algorithm to take into account real-world effects on spray droplets targeted at overhead flowers. To test the algorithm modifications, a simulation was performed using several different robotic platform velocities to test the effectiveness of the system. These results were then compared to a statistical analysis to ensure their validity.

Keywords: agriculture, algorithms, Monte Carlo simulation, probabilistic models

1. INTRODUCTION

When designing a system to deliver spray to a given target, the behavior of spray droplets is an important consideration as the motion of the spray once it leaves the nozzle affects where and when the spray will land. For example, both the initial magnitude and direction of the spray velocity needs to be taken into consideration when modelling the spray trajectory. Further, the spray itself is subject to effects such as gravity, drag, and wind that must also be taken into consideration when deciding when to command a nozzle to spray. This paper discusses the equations used to model the droplet behavior and the effect of the spray trajectory on system performance.

The application motivating this paper is shown in Fig. 1 and consists of a moving robotic platform actuating spray nozzles at target flowers as they pass. Targets are randomly distributed in the test environment and their locations are not known in advance. Instead, the location of each target is determined by a camera pair in real-time as the platform passes. The goal of this application is to approach the value of 100% of targets hit when the sprayers were on continuously. However, the material to be sprayed should be minimized and only the amount needed by each target should be used; thus, the goal of the scheduling algorithm is amended to hit 95% of targets while using the minimum amount of spray material. This value was chosen as an estimate of the number of flowers that can be seen and reached from a robotic platform travelling below the flowers. There is no limit on the number of sprayers that can fire at once, but only one sprayer should fire at each target. This means that there is a single opportunity to hit each flower so the spray must be aimed precisely.

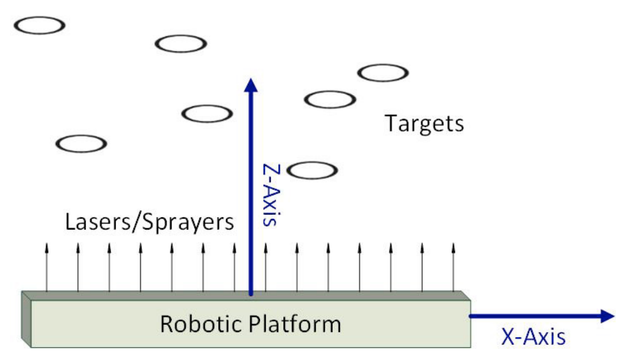

Fig. 1. A diagram of the robotic system application. The y-axis is in the direction of the platform's movement and forms a right-handed coordinate system.

The requirement that this system is capable of at least 95% target coverage leads to the inclusion of a coverage area problem where the goal is to determine how to cover the targets in the most effective manner. Osterman et. al. (2013) examined this problem for an orchard application where three robot arms were used to spray pesticides on trees. A LIDAR system was used to obtain canopy measurements in real-time and a positioning algorithm was used to determine the position and orientation of the three arms that would result in the maximum coverage of the near side of a tree. This work was an improvement upon an earlier model developed by Hočevar et. al. (2010) which used an RGB camera to obtain canopy measurements and made use of threshold values to determine whether to spray with a given nozzle.

In the application presented in this paper, the linear array of spray nozzles is not moveable in segments. Thus, the coverage area problem was explored by using images of the canopy to determine when to turn on each nozzle. This allowed the spray nozzle array to meet the coverage requirements while constrained to a fixed physical shape.

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Each target was assigned to the nearest sprayer based on a geometric analysis. The target's place in the individual spray nozzle queue was found by comparing the current robotic platform position with the calculated target position. This allowed the queuing system to be flexible since it made use of environmental feedback to schedule the spray nozzles.

This problem formulation is similar to a tracking problem with anticipation; the targets are tracked and the spray is fired to intercept the target's future position. This idea is applied in Hirsch et. al. (2011) to a varying number of unmanned aerial vehicles (UAVs) used to track six ground targets. The target motions were not known in advance and the UAVs independently determined their trajectories to minimize the tracking uncertainty over all targets by estimating the future position of the tracked objects. Charlish and Hoffmann (2015) explored this idea as applied to radar performance and assumed that the current state could not be fully known, but only partially observed through noisy measurements. A partially observable Markov decision process was used to anticipate the future position of the target so that the radar could follow a smooth path while keeping the target in range. The authors argued that selecting future actions based on the current state was not enough. Instead, future actions should be selected based on how the system was expected to behave in the future.

Similarly, Spletzer and Taylor (2003) used mobile camera systems to track one or more moving targets. The mobile camera systems had constrained velocities and their positions were limited by a minimum distance from the target. It was assumed that each mobile camera system knew its own position. Dynamic models of the target's motion were obtained using an approximation of the target dynamics. The mobile camera systems moved to minimize the target position estimate error at the next time instant based on the dynamic model.

In the method presented here, the droplet dynamics were modelled as accurately as possible so that the spray would reach the intended target as it passed above the robotic platform. As such, the trajectory of the spray was modelled as a parabola rather than as a simple straight line trajectory. This resulted in a more accurate representation of the real-world spray behavior and better prediction of the spray location at the time of impact with the canopy. Further detail of the scheduler algorithm used in this paper can be found in Section 2 and a description of the spray system can be found in Section 3. Section 4 provides details about the scheduler algorithm modifications while Section 5 provides the simulation results. Finally, the conclusions and future work can be found in Section 6.

2. SCHEDULER ALGORITHM OVERVIEW

The scheduler algorithm presented in this paper made use of a grid system to determine when to schedule spraying of flowers as they passed above the sprayer array. The flower locations were determined by a camera pair which made observations about the flower positions and supplied (x, y, z) locations in the local coordinate frame. The robotic platform velocity information was then used to assess whether each flower was within the designated grid spaces, and, if so, the flower was assigned to the nearest sprayer. This process was repeated for each flower located by the camera pair and a single binary command string representing each sprayer command was sent to the sprayer array. The algorithm was discussed in greater detail in a separate publication by Cashbaugh et. al. (2016).

For the simulations presented here, this algorithm was implemented in MATLAB 2014b on a conventional Pentium-class workstation running Windows 7. The workstation had a 2.70 GHz processor and 8.00 GB of RAM and ran the algorithm in less than 5 ms.

3. SPRAY SYSTEM DESCRIPTION

The spray array for this application consisted of 90 spray nozzles spaced evenly along a linear boom. Each nozzle emitted a spray cone with a small interior angle, consisting of droplets with a known mean diameter and velocity at the nozzle exit. These spray nozzles pollinated the flowers using a mixture of water and pollen with properties very similar to that of water itself.

The targeted performance value of the spray system was to hit 95% of the flowers within reach of the platform. All simulations and physical experiments discussed in this paper were evaluated with this performance criteria in mind and only trials that achieved a 95% hit rate were considered to be successful trials. It is important to note that 95% of the flowers needed to be hit, not pollinated. This is an important distinction since pollination requirements are not immediately obvious and require further investigation. For example, Campbell and Haggerty (2012) claim about 13,000 pollen grains per stigma are required for successful pollination while Hii (2004) claims about 3000 to 4000 grains per stigma are required for the desired export weight of 70 g.

4. SCHEDULER ALGORITHM MODIFICATIONS

Several modifications to the algorithm developed by Cashbaugh et. al. (2016) were necessary in order to use this algorithm for the application discussed in this paper. Previous versions of this scheduling algorithm were designed to work with a laser system, but laser beams are not subject to gravity, wind, or drag and so are easier to schedule and simulate. However, liquid spray is subject to such physical parameters, requiring further scheduler modifications to take these effects into account.

The effect of gravity was taken into account using the following formula for simple projectile motion:

$$h_t = -\frac{1}{2} * g * t_h^2 + v_d * t_h \tag{1}$$

Here, h_t is the height of the target in m, g is the gravitational acceleration of 9.81 m/s^2 in the negative z direction, t_h is the time it takes for the droplet to reach the target height, h_t, in seconds, and v_d is the initial droplet velocity in m/s in the positive z direction. This equation was then solved for time to obtain (2).

$$t_h = \frac{v_d \pm \sqrt{v_d^2 - 2 * g * h_t}}{g} \tag{2}$$

Although mathematically there are two solutions to equation (2), only one solution was used in practice. This was because the trajectory of the drop follows a parabola as shown in Figure 2. The droplet reaches a height of h_t twice in this trajectory: once on the way up and once on the way down. The drop should impact the target from below, thus necessitating using the drop's position on the way up, the $t_h = \frac{v_d - \sqrt{v_d^2 - 2*g*h_t}}{g}$ formulation.

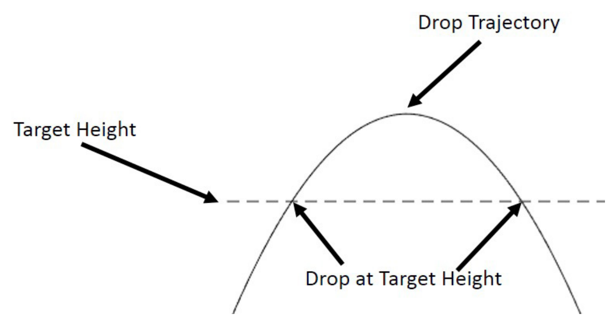

Fig. 2. This plot shows the droplet trajectory and the target height.

Next, the forward motion of the robotic platform was taken into consideration by calculating how far along the robotic platform's trajectory the drop would move in time t_h as the drop rose to target height.

$$d_h = v_r * t_h \tag{3}$$

In this equation, d_h is the distance in m travelled between the drop's release to the time it hits the target, v_r is the robotic platform velocity in m/s, and t_h is as defined above. This distance was then broken down into its x and y components using the global coordinate frame and robotic platform heading, α, shown in Figure 3. The resulting equation is shown below in equation (4).

$$\begin{bmatrix} d_{h,x} \\ d_{h,y} \end{bmatrix} = d_h * \begin{bmatrix} -\sin\alpha \\ \cos\alpha \end{bmatrix} \tag{4}$$

These two components are then subtracted from the global (x, y) target position to account for the platform velocity, resulting in the actuators firing early enough so that the spray can intercept the target trajectory as the robotic platform moves at a constant velocity.

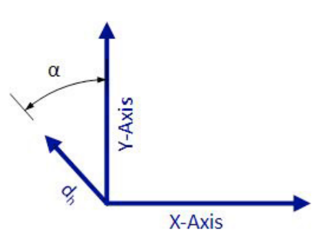

Fig. 3. The coordinate frame used by the scheduler and the rig's direction of motion.

Drag was found to have a negligible effect on the droplets at such short distances and so was not considered for scheduling purposes. To verify this assumption, drag was considered when evaluating whether or not the spray hit the target using equations (5) through (8) below [Morrison (2013)].

$$wind_{rel} = \sqrt{(wind_x - v_x)^2 + (wind_y - v_y)^2} \tag{5}$$

$$Re = \frac{\rho_{air} * d * wind_{rel}}{\mu_{air}} \tag{6}$$

$$c_d = \frac{24}{Re} * (1 + \frac{1}{6} * Re^{0.66}) \tag{7}$$

$$D = \frac{1}{2} * \rho_{air} * (wind_{rel}^2) * c_d * \pi * \frac{d^2}{4} \tag{8}$$

In these equations, $wind_x$ and $wind_y$ are the wind velocity components in the x and y directions, respectively. Similarly, v_x and v_y are the robotic platform velocity components in the x and y directions, respectively. The density of air, 1.225 kg/m^3, is represented by ρ_{air} while the air kinematic velocity of $1.5e^{-5}$ m^2/s is represented by μ_{air}. Finally, d is the droplet diameter.

5. SIMULATION RESULTS

In the simulations presented here, each actuator was assigned an (x, y, z) location in the local coordinate frame. The robotic platform was assumed to have a constant velocity which it maintained for the duration of the simulation as it moved in a straight line along the y-axis. 1,375 target flowers with a diameter of 0.02 m were randomly generated using a uniform distribution random number generator anywhere within a 2 m by 5 m by 2.25 m test area. The domain spans a distance of 100 target diameters so any issues arising from targets at the domain edge are trivial. This size test area was chosen because it had the same length and height as the fake canopy designed for testing the hardware; the width was chosen to match the boom width so that all targets could theoretically be hit when the robotic platform was travelling in a straight line.

The simulation was iterated using a time step of 0.005 second determined by the command frequency of 200 Hz. At each time step, the location of each spray was evaluated to see whether or not it hit a target. If the spray (x, y) location was within a target's radius of the target center, then the spray was considered to be a "hit" and contributed to the total percent of targets hit. Once a target was hit, it was removed from further consideration in order to avoid double counting targets. The robotic platform velocity was varied from 0.1 m/s to 2.5 m/s in increments of 0.1 m/s. At each velocity, 100 simulations were run with different target positions and the mean percent of targets hit was calculated. The results of these simulations are discussed and compared to the results achieved through a Poisson statistical analysis developed by Bradley (2015).

To verify the results of the simulation via comparison with a statistical analysis, a full run was performed using point coverage spray areas for each spray nozzle. This meant that all of the droplets in the spray hit the target at exactly the same place. The statistical analysis [Bradley (2015)] does not take spray coverage area into account, so

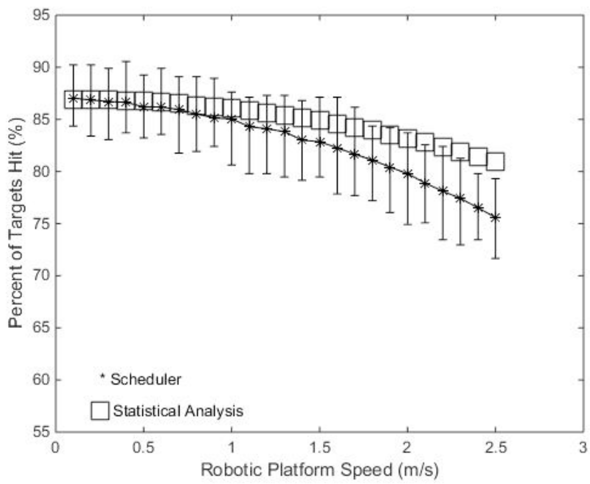

Fig. 4. Plot of the robotic platform speed vs. the percent of targets hit using a point spray coverage area.

the use of a point coverage area was necessary in order to perform a valid comparison between the results. These results are shown in Fig. 4 and reveal that, as the platform gained speed, the simulation resulted in increasingly fewer target hits than predicted by the statistical results. This is as expected since the simulation took into account more real-world considerations. While the modelling does not perfectly match real-world conditions, work is planned to improve the model. Figure 4 also shows that the difference between the simulation and statical results reaches its midpoint at 1.6 m/s. This decrease in performance is posited to be due to the increased effect of drag on the droplet's motion as the droplet's relative speed increases with the speed of the robotic platform. In fact, this finding agrees with that in Cashbaugh et. al. (2016) which recommended a speed limit of 1.6 m/s for the robotic platform based on system performance. After this speed, the effect of drag is no longer negligible and should be taken into account.

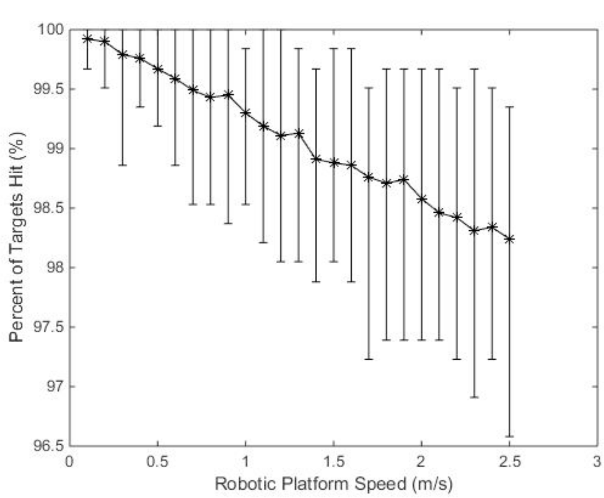

Fig. 5. Plot of the robotic platform speed vs. the percent of targets hit using the actual spray cone coverage area.

Since the spray nozzles actually emit a small angle spray cone rather than a point spray, a second simulation run was performed to gauge the system's performance in an orchard environment. These results in Fig. 5 illustrate that the desired system performance results of 95% coverage are easily met at all robotic platform speeds. This is because the spray cone is large enough to provide total coverage across the width of the boom. Targets are missed due to the fact that the nozzles fire in bursts at the beginning of each grid space rather than continuously. This means that if a target is located at the farther end of a grid, it may not be able to be sprayed. Additionally, the fact that some spray may hit multiple targets was not accounted for in this model. This consideration is planned to be examined more closely in future work. However, the results indicate that the spray system is able to be successfully adapted to real-world conditions and real orchard testing can be performed in the November 2016 season.

6. CONCLUSIONS AND FUTURE WORK

Because pollination season is limited, the simulation results were useful for determining the algorithm's effectiveness before the season began. This allowed the authors to explore different parameters and wind conditions without wasting expensive pollen, leading to more effective experimentation in the orchard. The results indicate the the algorithm is able to be successfully adapted from a laser-based test system to a real-world spray system.

Future work is planned to test this algorithm in a real orchard environment in the 2016 season. In preparation for such a test, future work is also planned to perform small scale testing of the scheduling algorithm with the spray nozzles in a controlled environment.

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