


Stippling with aerial robots

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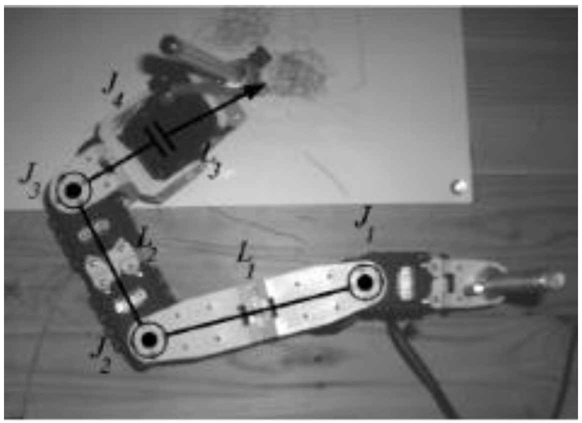
Introduction

Introduction

Drawing with robotics



TRESSET P (2013) Portrait drawing by Paul the robot.

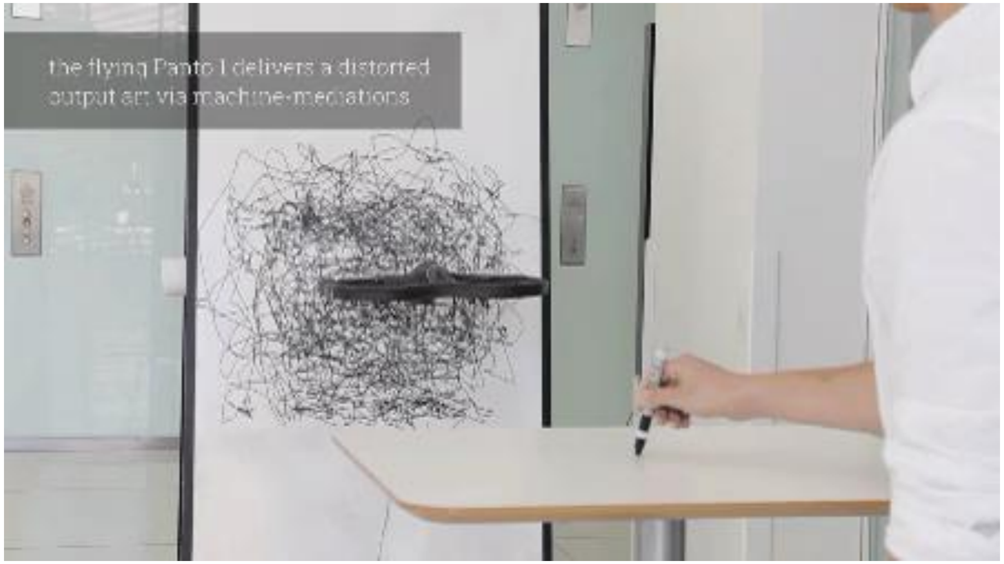
LEHNI J (2002), Hektor: Diploma project at ECAL

LIN C.-Y (2009) Human portrait generation system for robot arm drawing.

LINDEMEIER T (2015), Hardware-based non-photorealistic rendering using a painting robot.

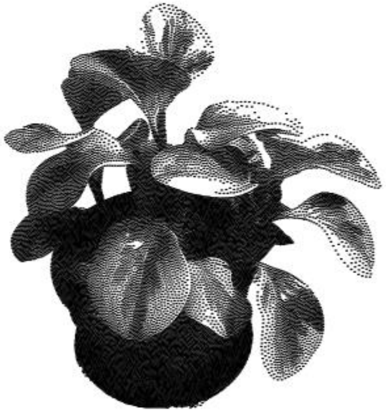
Flying robots in Art

SRIKANTH M (2014), Computational rim illumination with aerial robots.



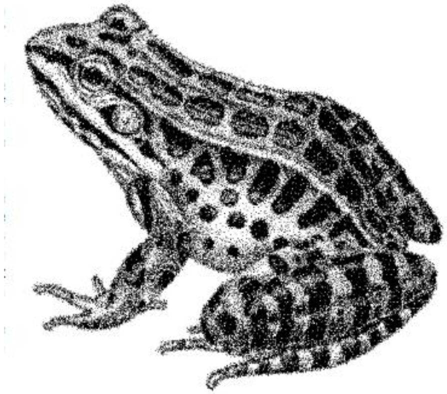
Sketchy MIT Media Lab

Stippling

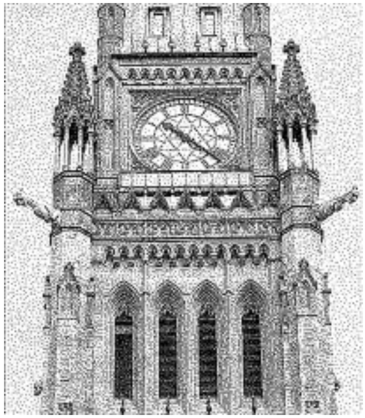


SECORD A (2002) Weighted Voronoi stippling

MOULD D (2007), Stipple placement using distance in a weighted Graph

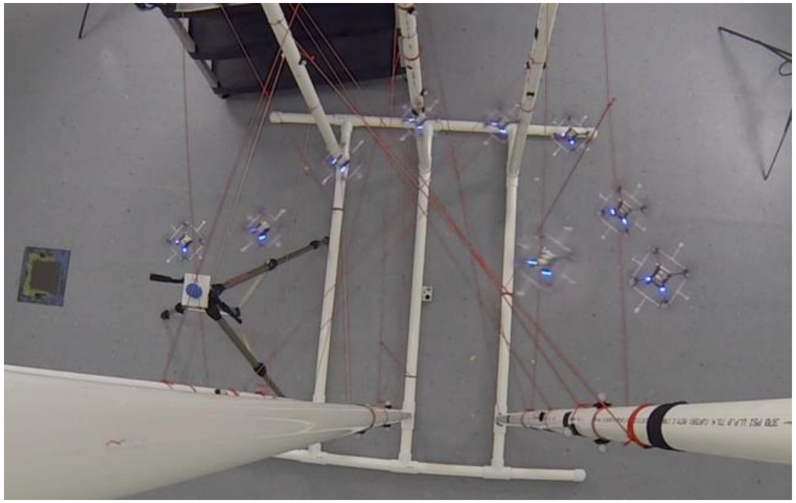


KIM S (2009), Stippling By Example



LI H., MOULD D diffusion (2011), Structure-preserving stippling by priority based error

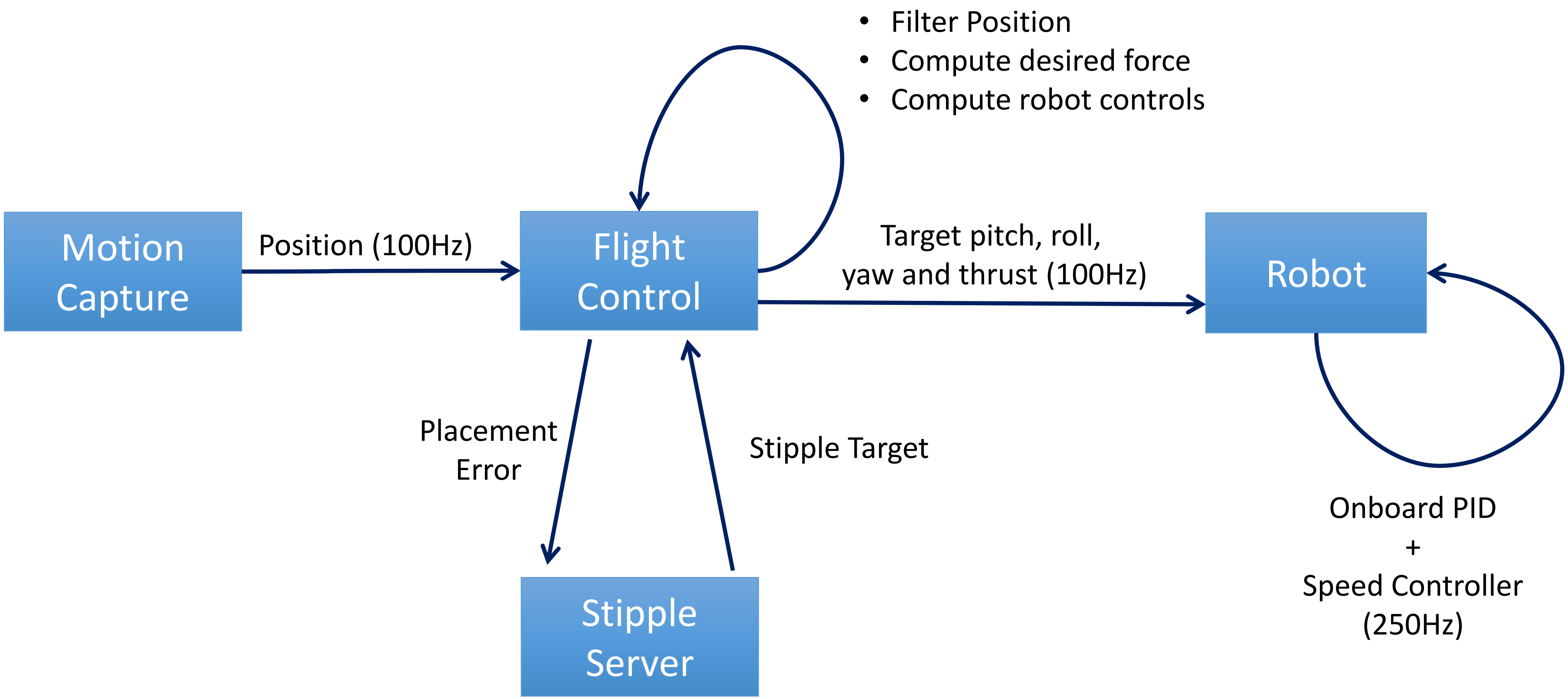
Aerial robot control



LANDRY B (2015), Planning and control for quadrotor flight through cluttered environments.

MELLINGER D (2012), Trajectory generation and control for precise aggressive maneuvers with quadrotors.

Our Approach

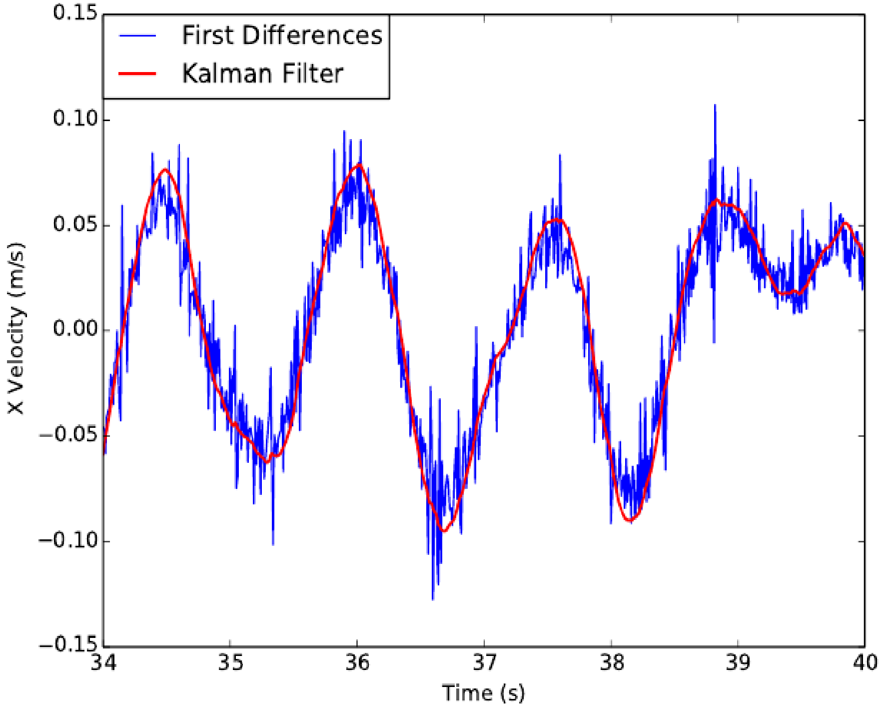


Quadrotor model

- Point mass model
  - align its pitch and roll instantly
- Offline system identification
  - Mass (30.0 grams)
  - No Inertia Tensor
  - Motor thrust calibration

Kalman Filtering and State prediction

- Smooth's position measurements from motion capture
- Provides velocity
- Predicts future state to counter system latency



Position Control

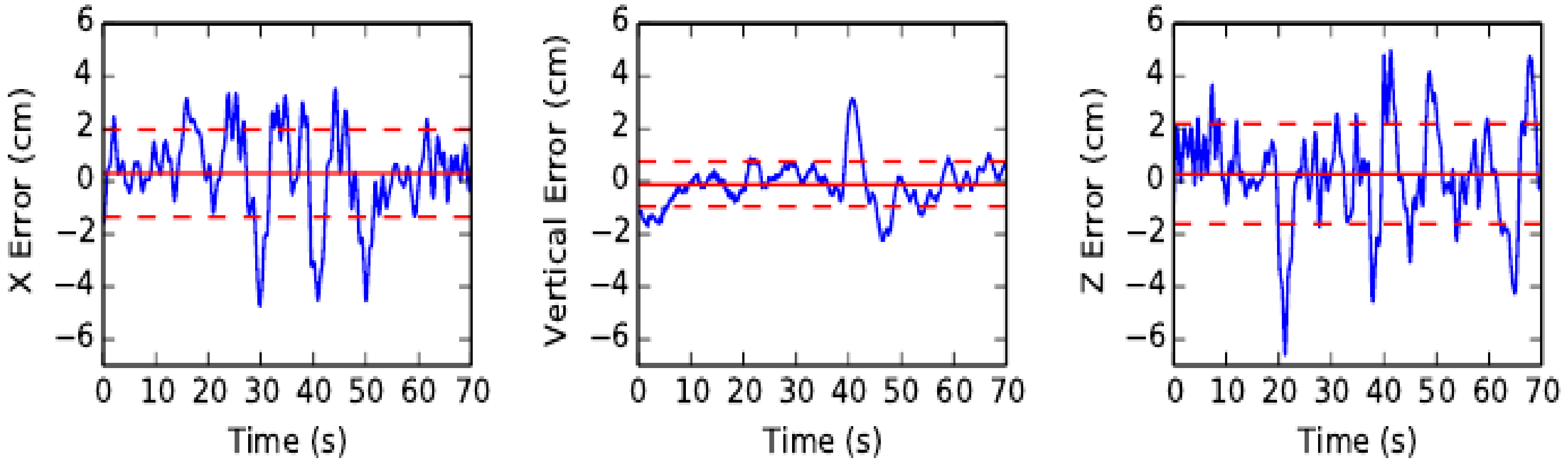
- PID controller to reach and maintain a desired position
- Computes desired net force acting on quadrotor

$$F_{\text{net}} = k_P(x_t - x) + k_I \int (x_t - x) + k_D(\dot{x}_t - \dot{x})$$

- Send desired roll and pitch commands so the quadrotor is aligned with the force vector

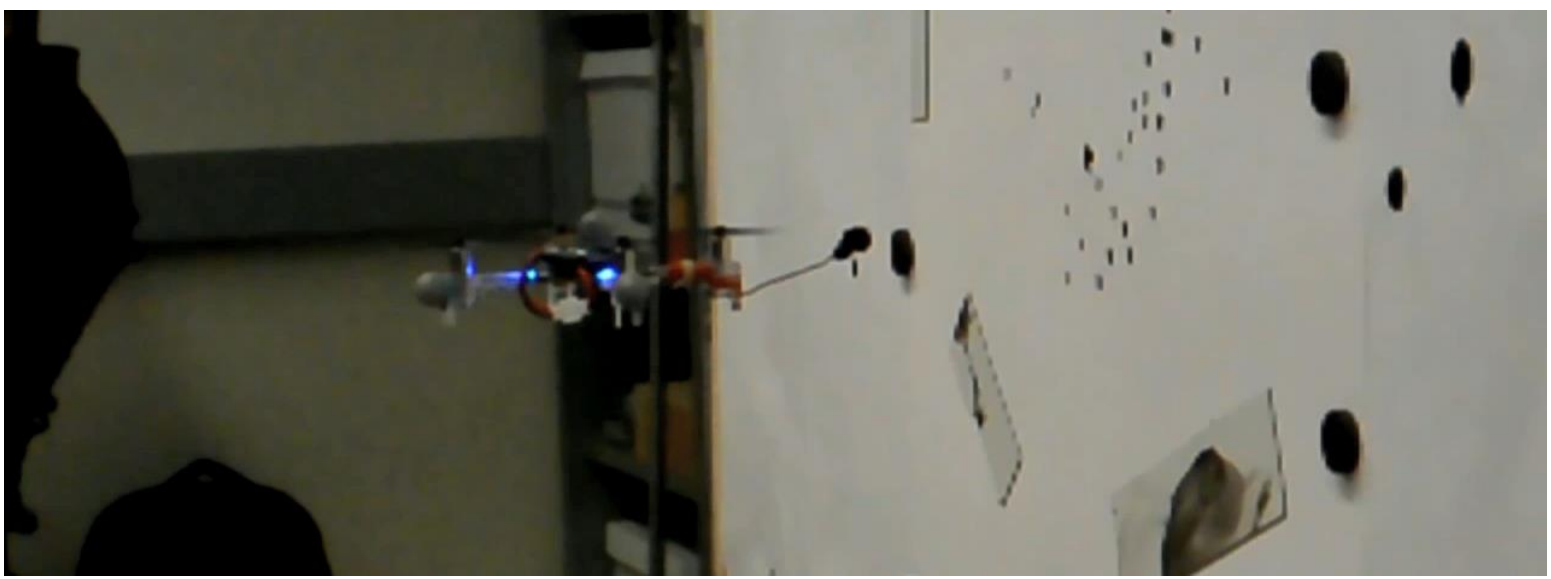
Hover Results

- position error of quadrotor from target location over time
- Solid and dotted red lines show the mean and standard deviation of the error respectively



Stippling

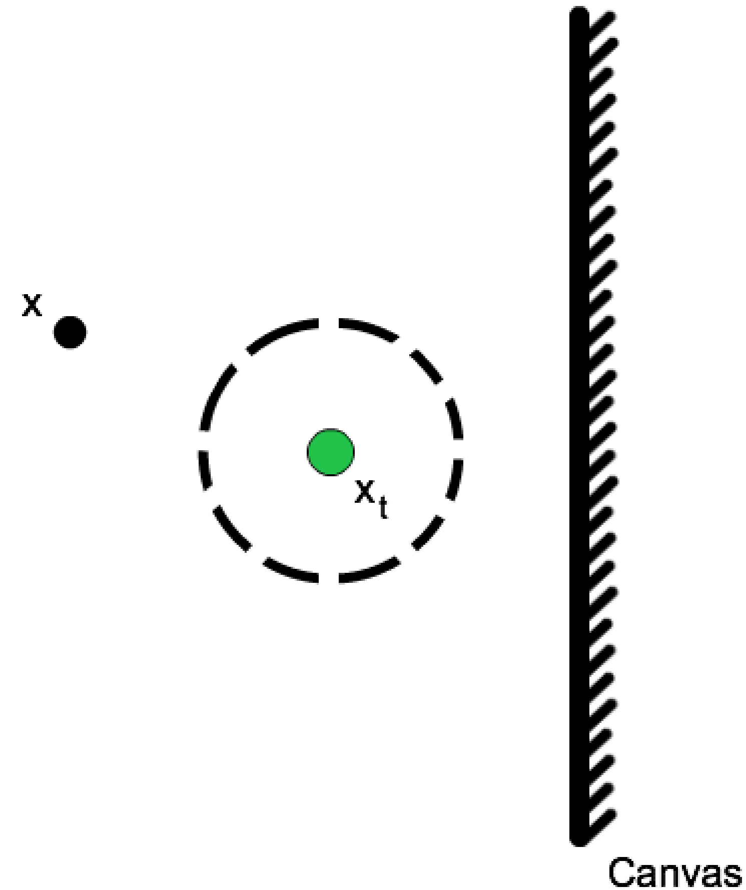
- Consists of 3 stages
  - Preparation
  - Stipple action
  - Recovery



1/16x Speed

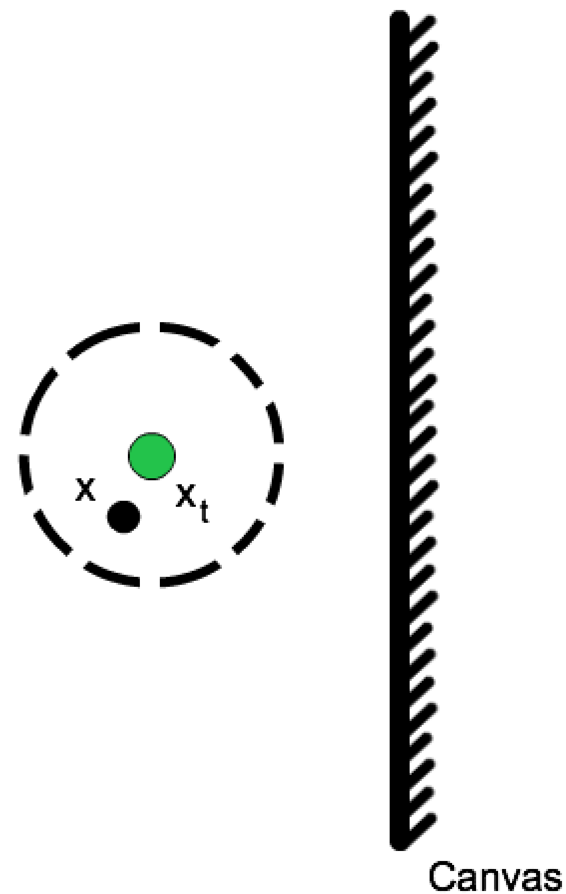
Stippling - Preparation

- Uses hover controller to approach point normal to target canvas location
- Only proceeds to stippling when hover error is below the desired accuracy threshold



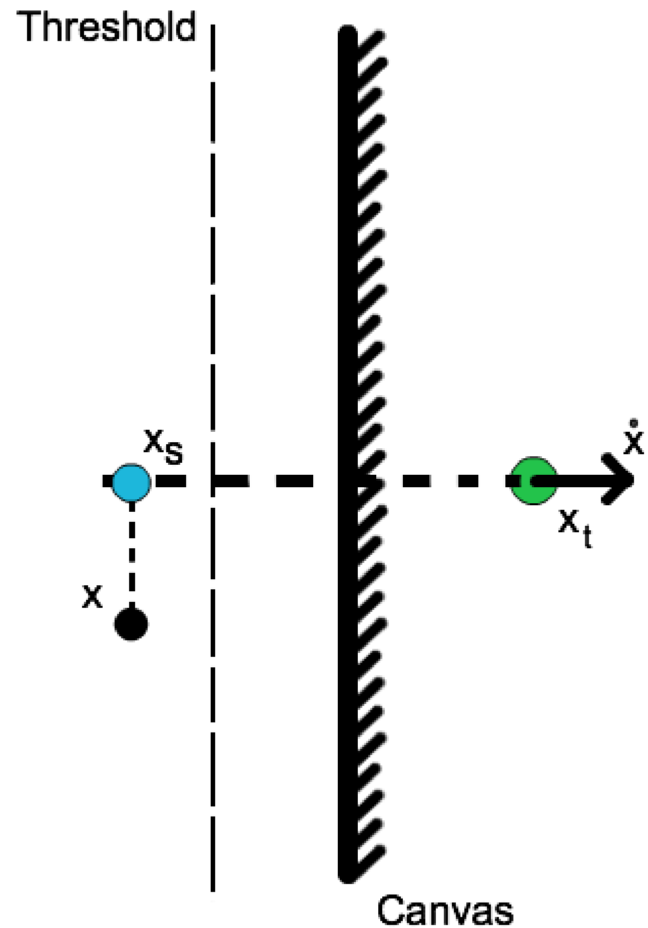
Stippling - Preparation

- Uses hover controller to approach point normal to target canvas location
- Only proceeds to stippling when hover error is below the desired accuracy threshold
- Tradeoff between time and accuracy



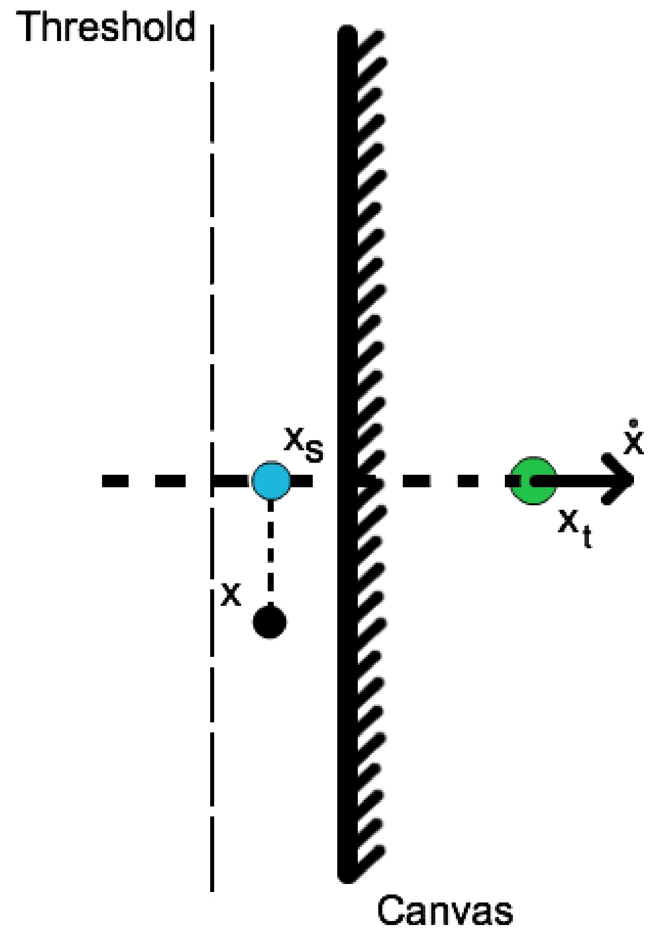
Stipple Action

- Uses an additional PD controller in combination with normal position control
- Acts on errors projected into plane of canvas



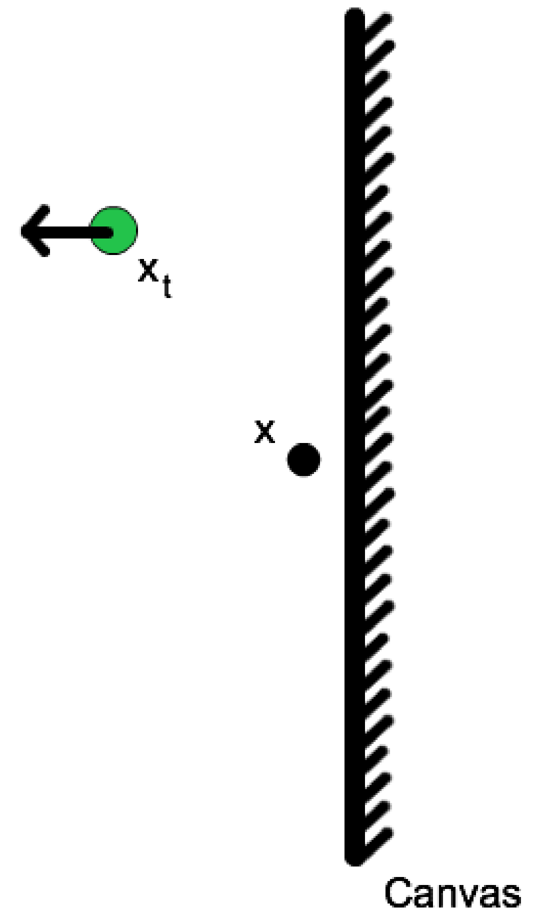
Stipple Action

- Uses an additional PD controller in combination with normal position control
- Acts on errors projected into plane of canvas
- Detects stipple when distance to canvas below threshold

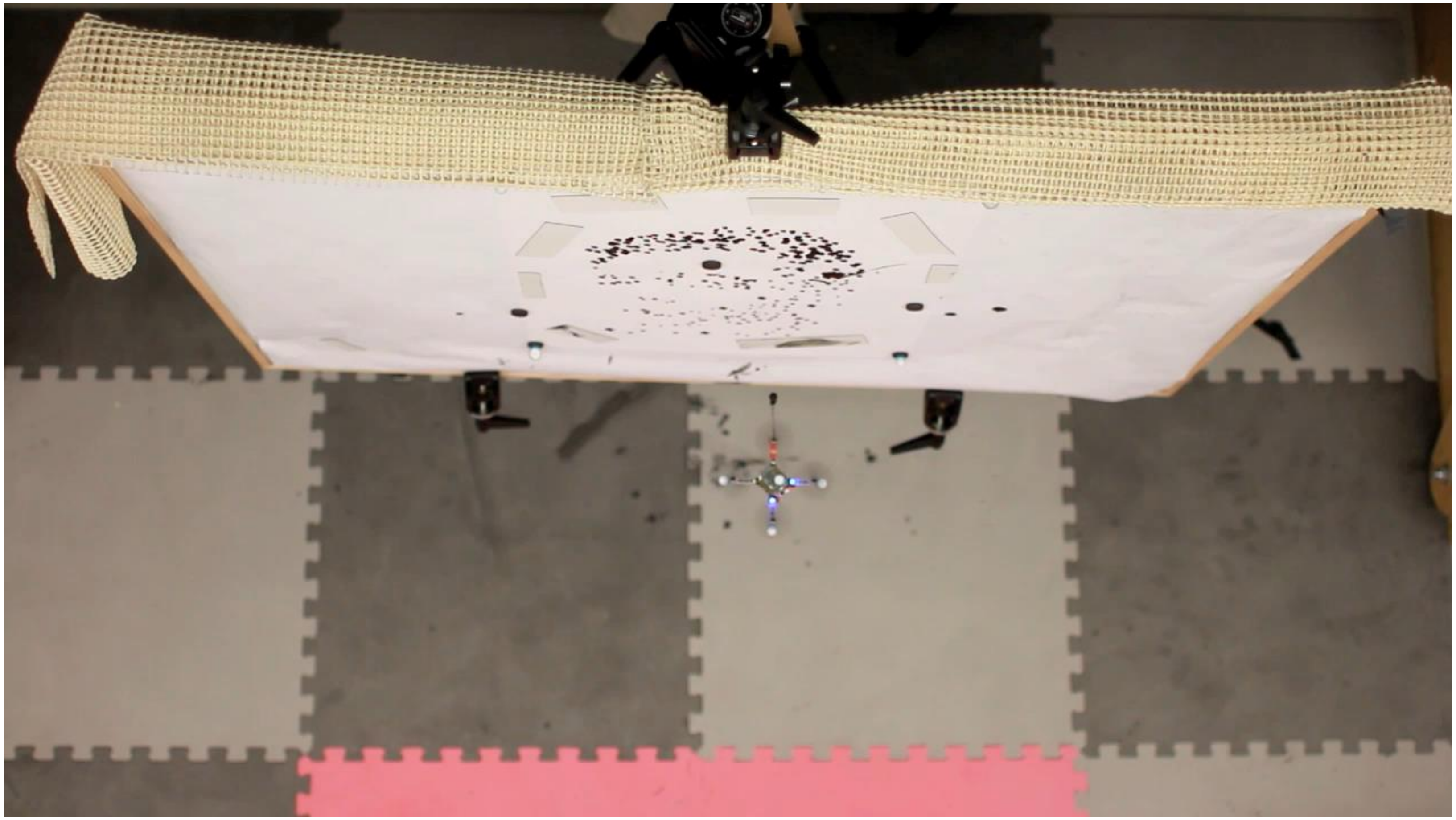


Stippling - Recovery

- Target location near next stipple location
- Lasts 50ms
- Sets target velocity away from canvas



Stipple video Turing



Radio Communication Improvements

- Existing communication not appropriate for real-time communication
  - Using queue with first-in first-out policy
  - Required ACKS with high retry count
  - Disconnect from quadrotor after retry count limit exceeded

- Improved protocol
  - Send most recent command, drop older commands
  - Lower retry count
  - ACKs required only occasionally before disconnecting

Software based speed controller

- Angular rotor speed generated by the motors is highly dependent on battery voltage
- Battery voltage decreases over time and fluctuates based on amount of current being drawn by the motors
- Proposed by Landry, runs onboard quadrotor and uses feedback on battery voltage

$$u = \frac{V_{\text{max}}}{V_{\text{actual}}} \left(\sqrt{\omega^2 - \beta} \right) + \alpha$$

Stipple Generation and planning

- High level planning for where to place stipples and in what order
- Dynamically adjusts future stipple placements based on reported errors of previous stipples

Stipple Generation

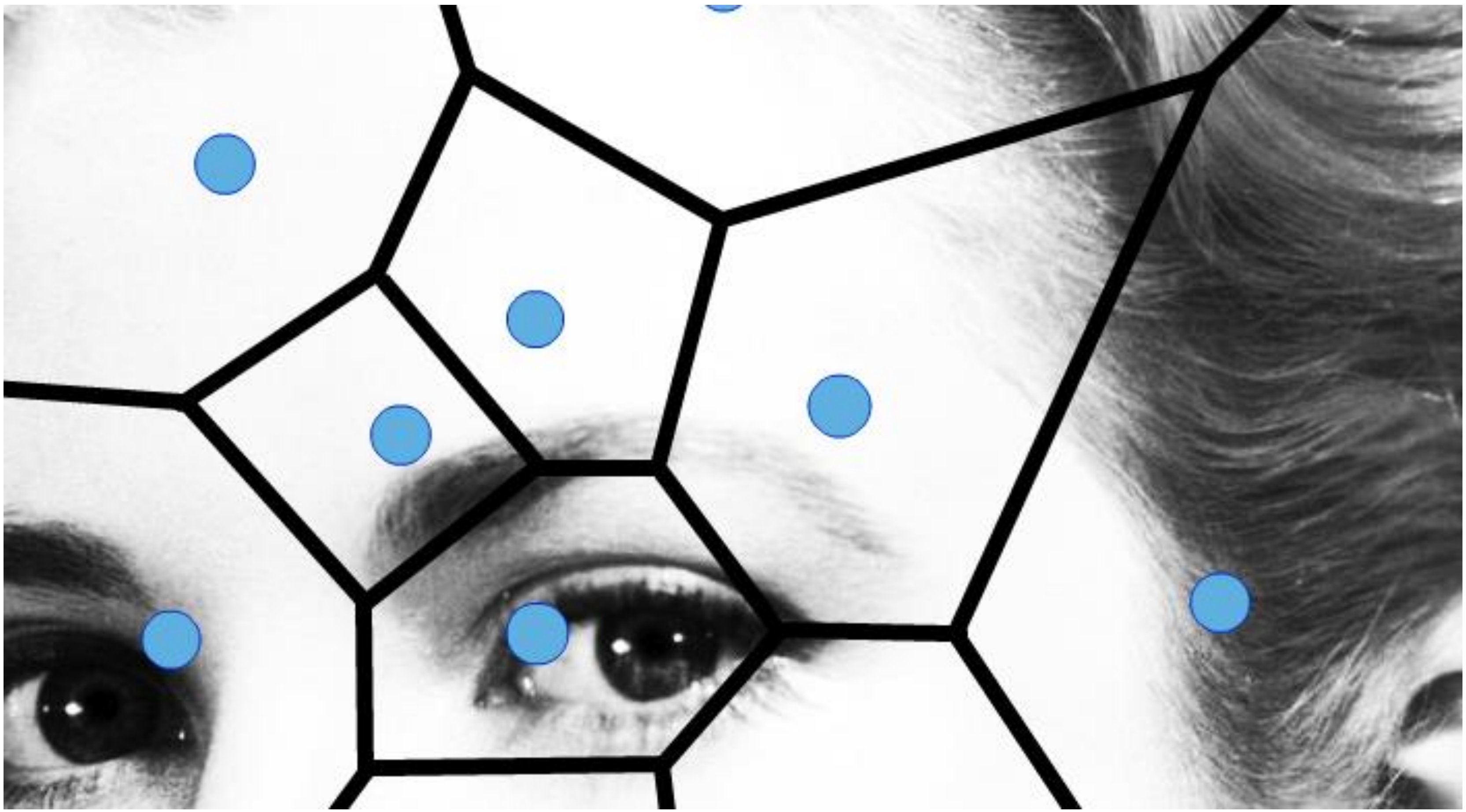
- stipple generation from a source image relies on weighted centroidal Voronoi diagrams (CVD)

CVD Algorithm
Start with initial random set of points
Until stable configuration is reached:
    compute Voronoi diagram
    compute region centroids
    shift points to centroids

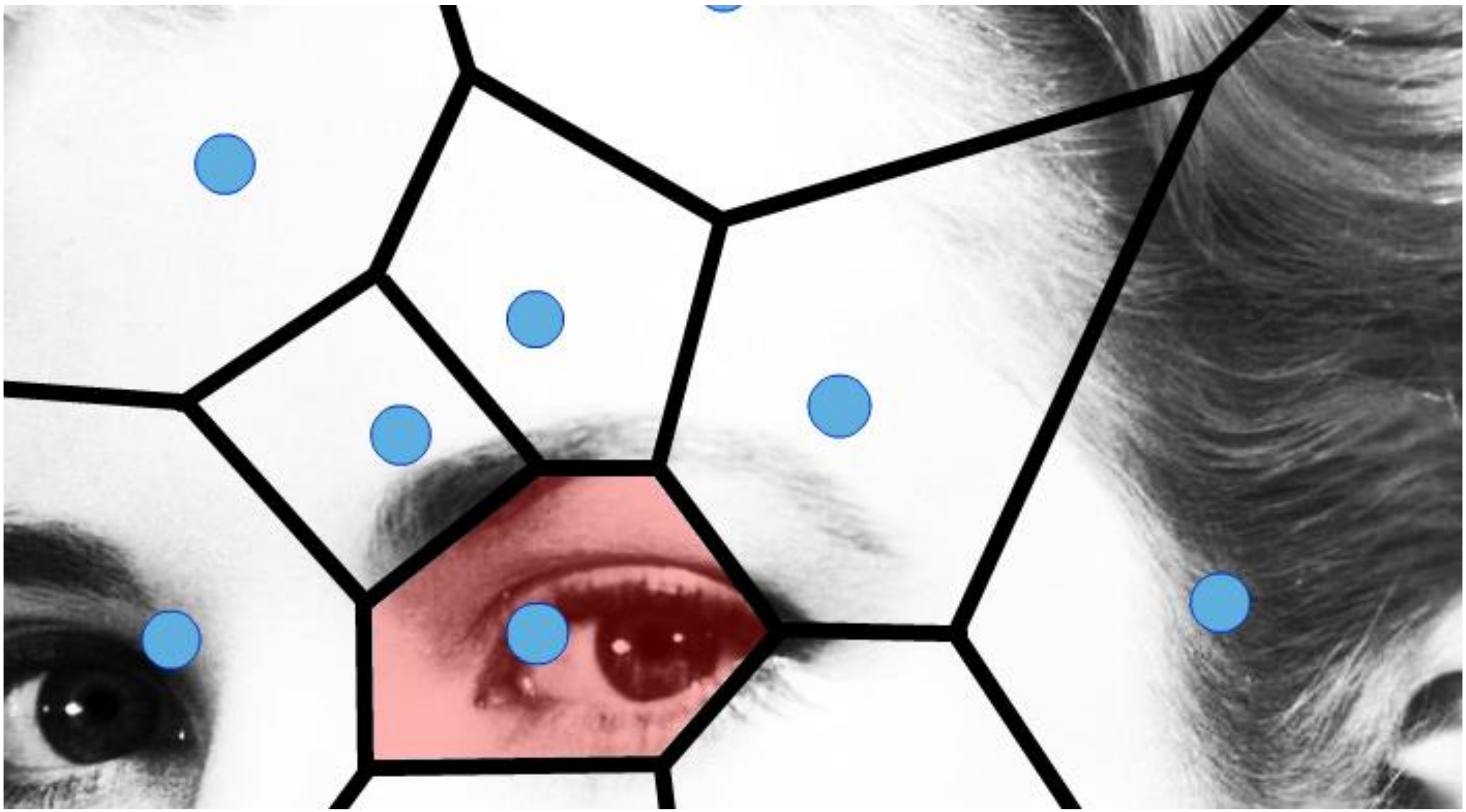
Stipple Generate

Stipple Generation

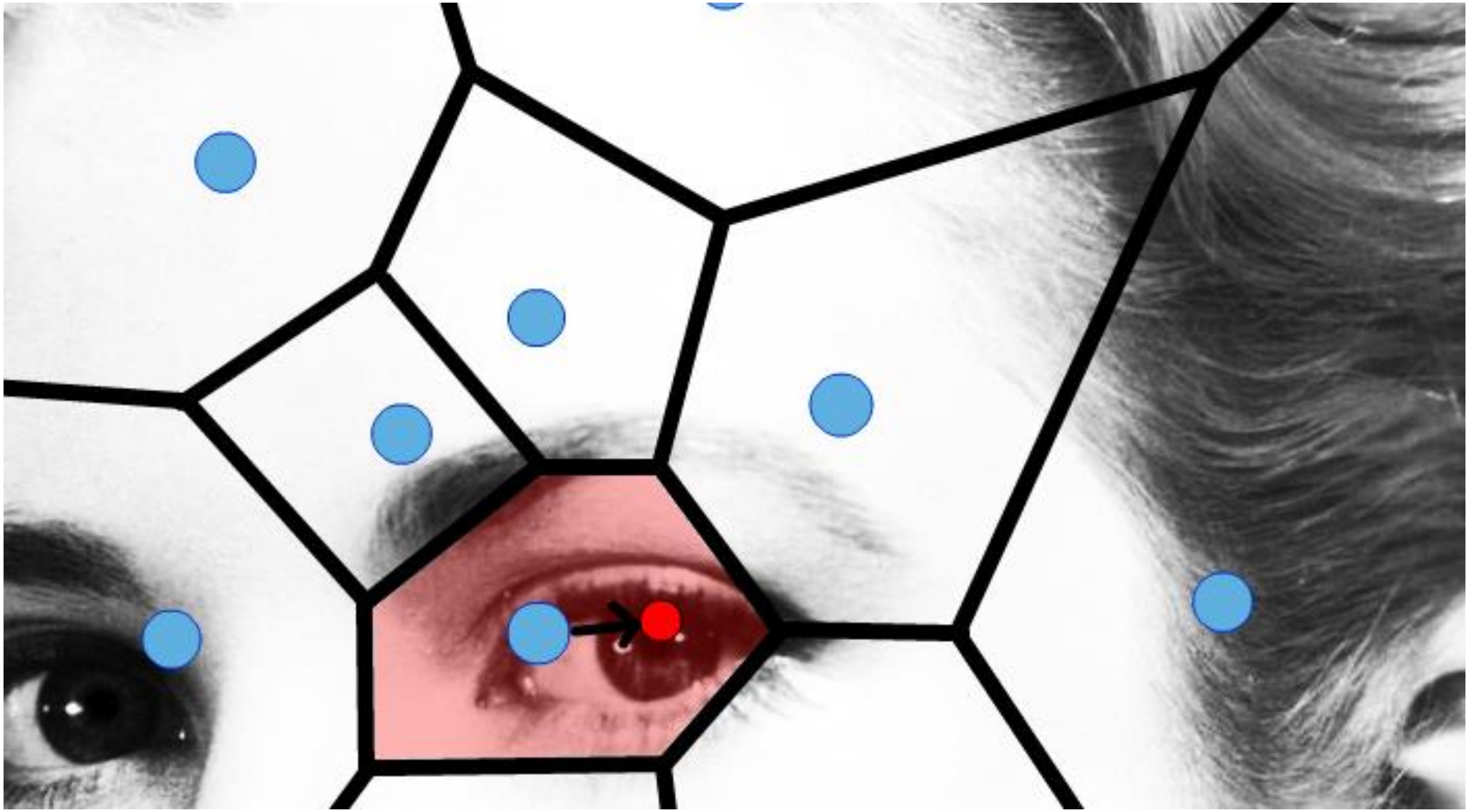
Stipple Generation



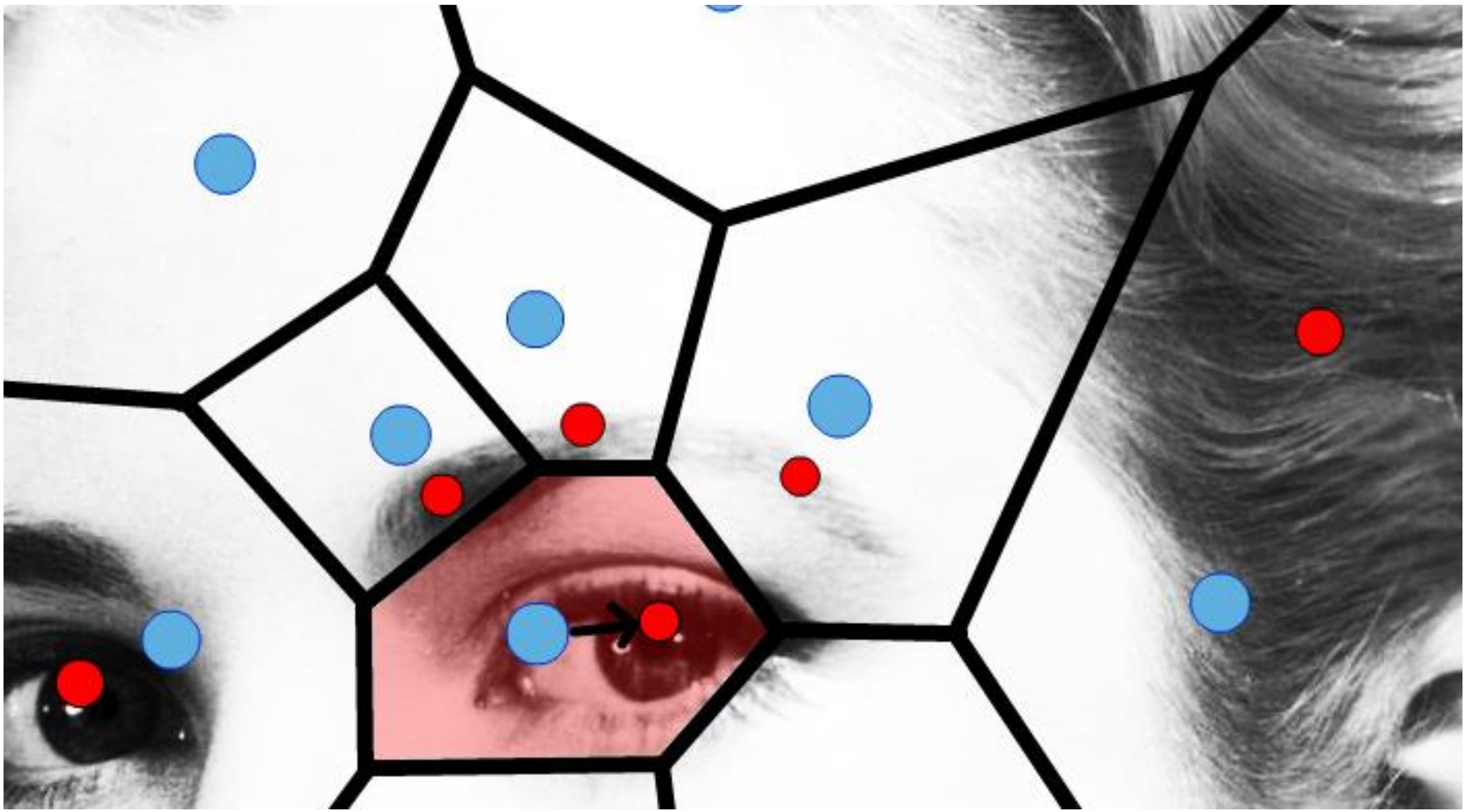
Stipple Generation



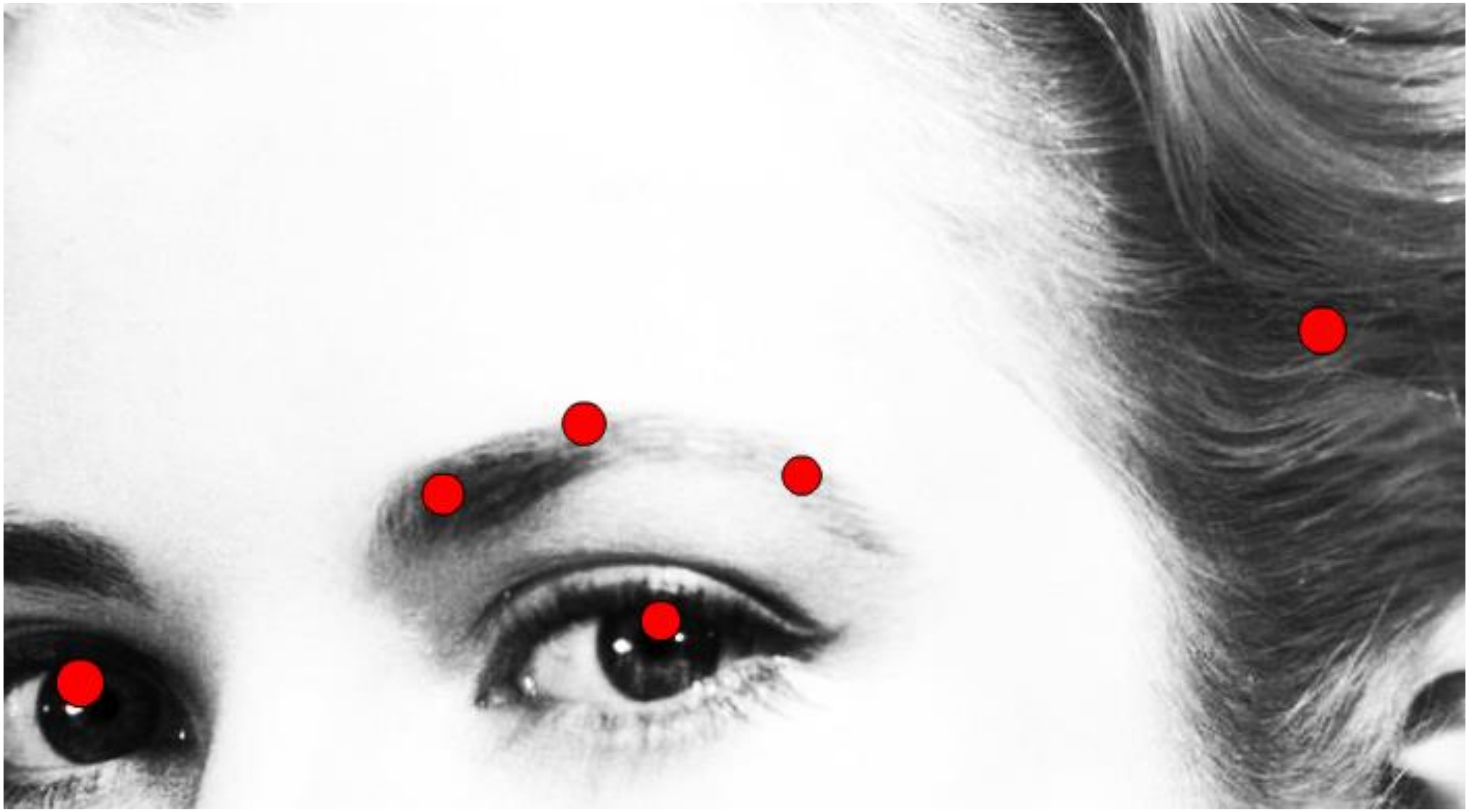
Stipple Generation



Stipple Generation



Stipple Generation

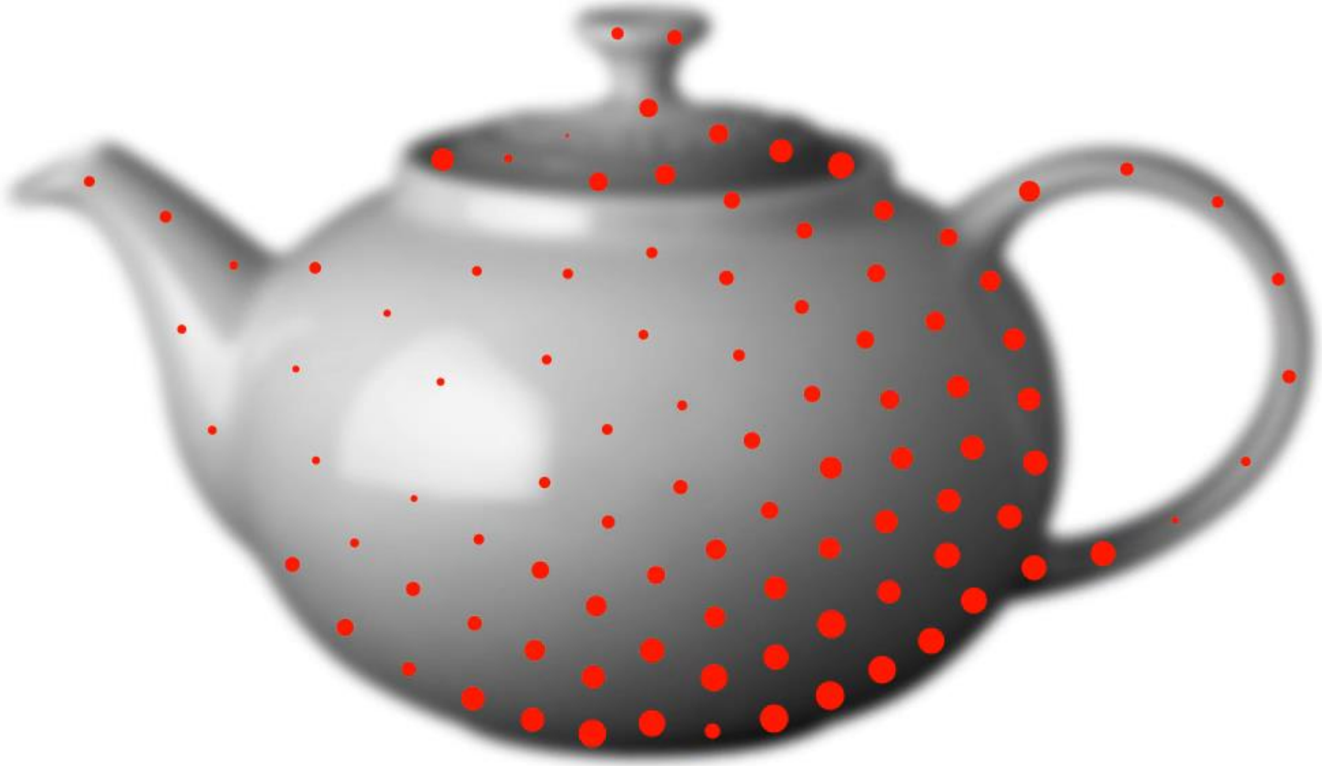


Stipple Generation

Dynamic Update

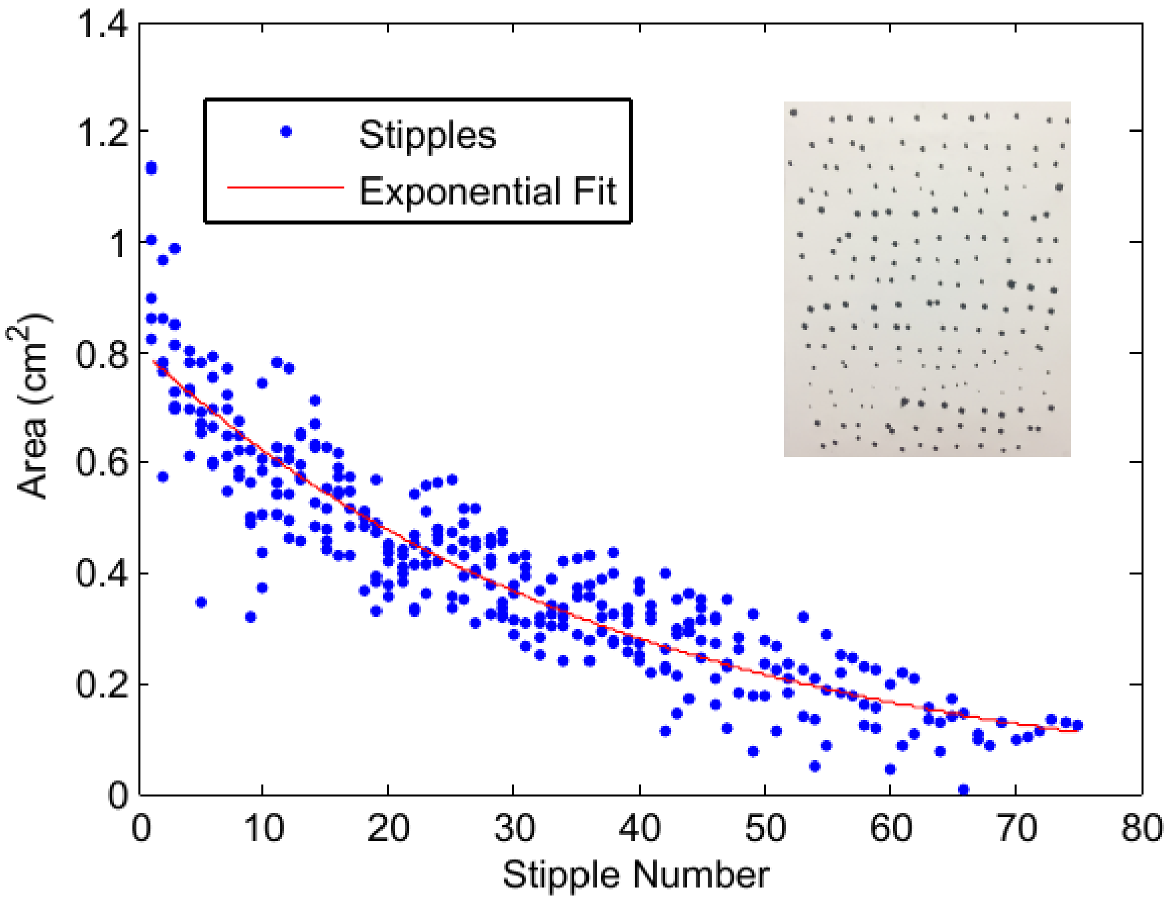
- Attempts to mitigate errors in stipple placement by adjusting location of future stipples
- Re-runs CVD algorithm with location of previous stipples fixed to update future locations

Dynamic Update



Ink Model

- Simplified model relies only on number of stipples drawn
- Used when planning the order that stipples should be drawn in



Stipple Size

- Linearly maps the average brightness for each region to a stipple size
- Minimum and maximum radii are computed using the ink model

$$r_i = \rho_i r_{\min} + (1 - \rho_i) r_{\max}$$

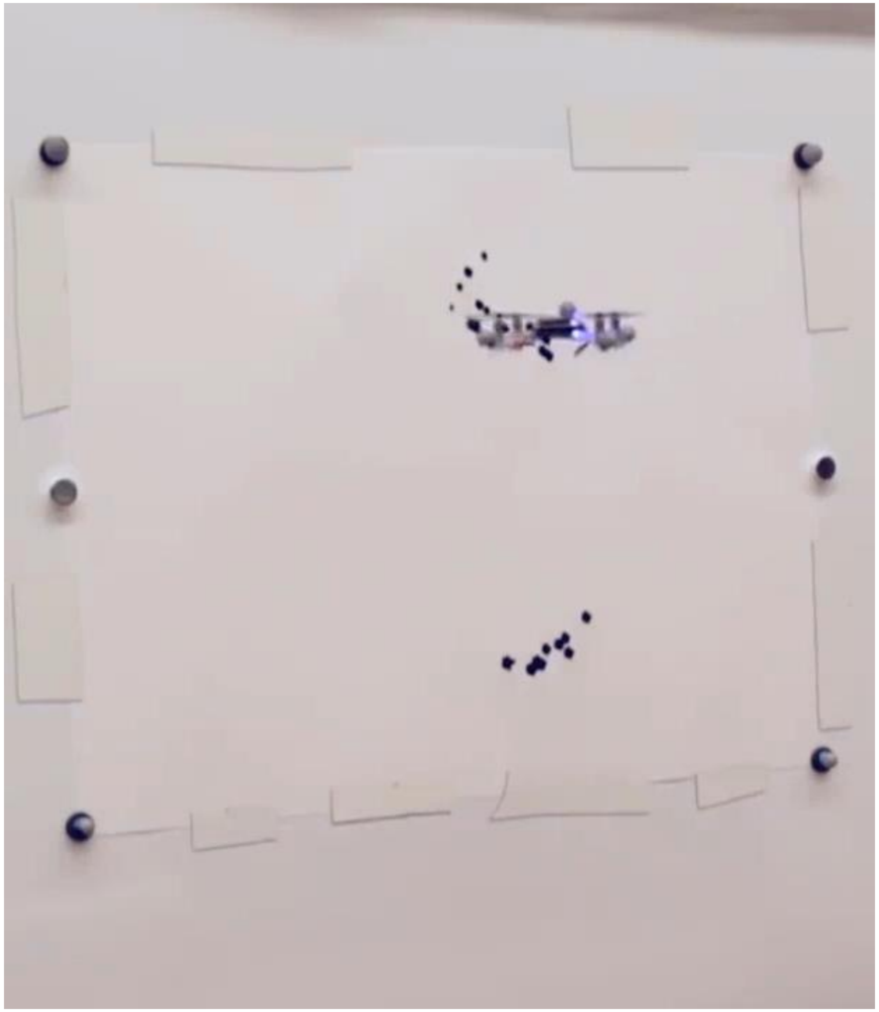
Where r_{min} and r_{max} are the minimum and maximum radii, and ρ_i is the average pixel brightness across region i

Path Planning

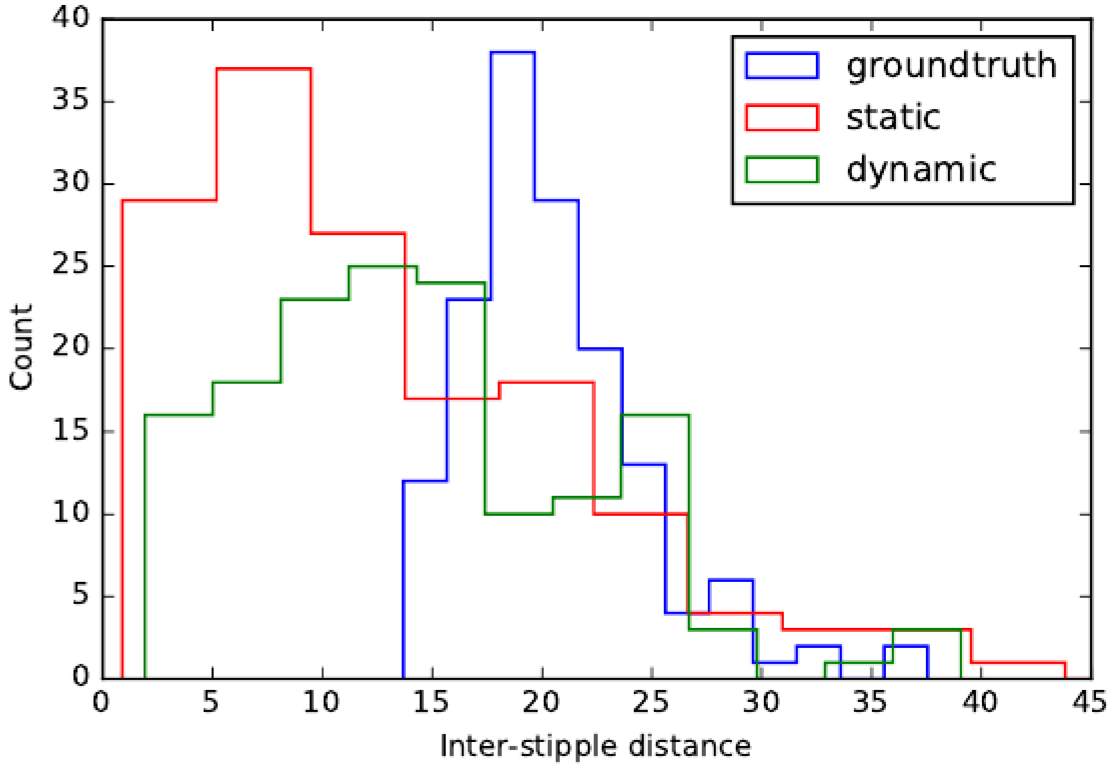
- Three main factors influence the order in which we want to draw stipples
  1. Minimize total distance travelled
  2. Match stipple size to ink model as best as possible
  3. Completed regions should be grown progressively to benefit from dynamic update

Path Planning

- Uses a greedy strategy for stippling ordering

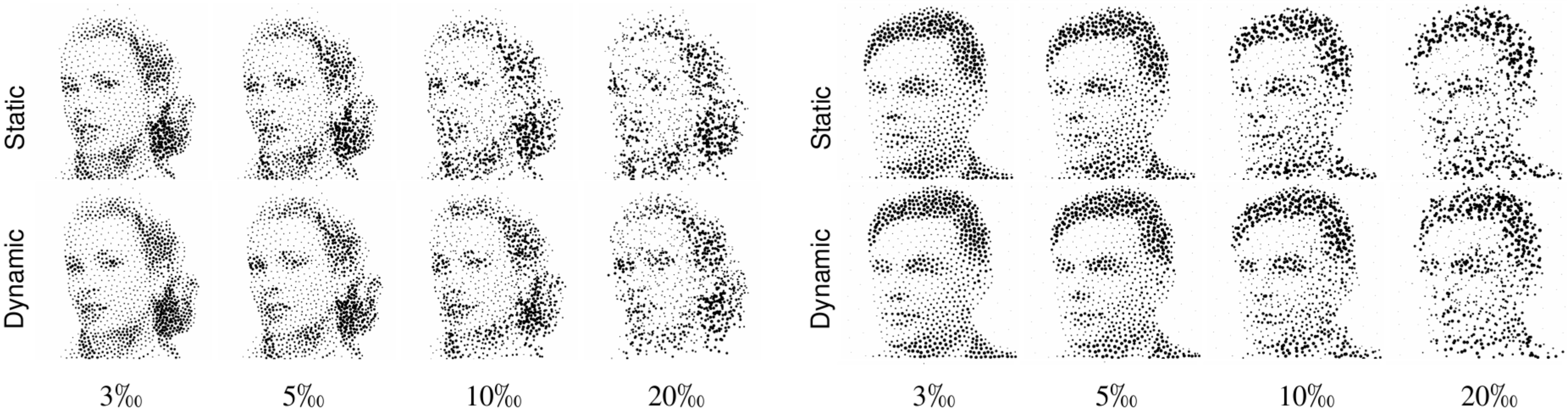


Dynamic Update – Synthetic Results



Histogram of the inter-stipple distance for the original output without errors (blue), the static stippling with error (red), and the dynamic error adjusted stippling (green), shown for stippling a teapot with 200 points and 1 % standard deviation Gaussian error.

Dynamic Update – Synthetic Results



Comparison of synthetic results showing stipples drawn with and without dynamic stipple placement correction for different amounts of error. Error standard deviation of stipple locations in different columns is shown as a per-millimeter of the canvas size.

Physical Prints

- Timing and error information for different prints

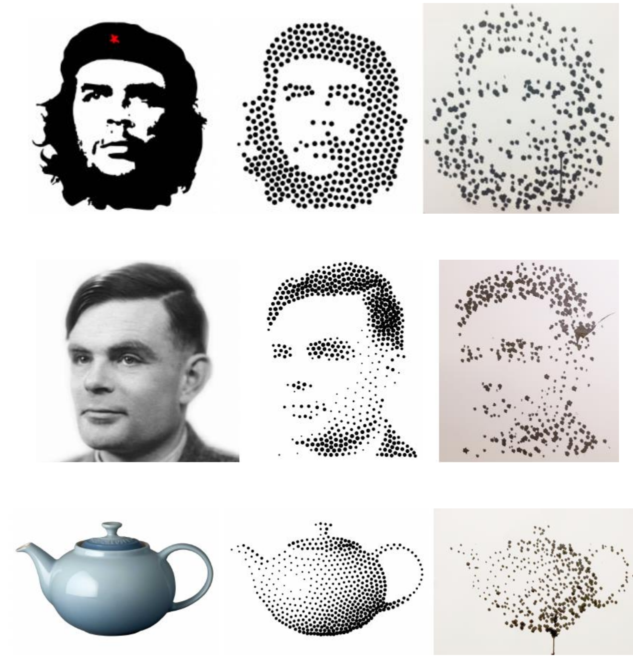


Image	t	μ_h	μ_v	σ_h	σ_v	n_f	$\bar{n}_s$
Che	6.7	1.70	-2.1	6.9	4.6	10	40
Turing	6.7	0.99	-4.1	6.6	3.8	8	62
Teapot	6.4	0.23	-3.1	7.9	4.2	10	50

Physical Prints

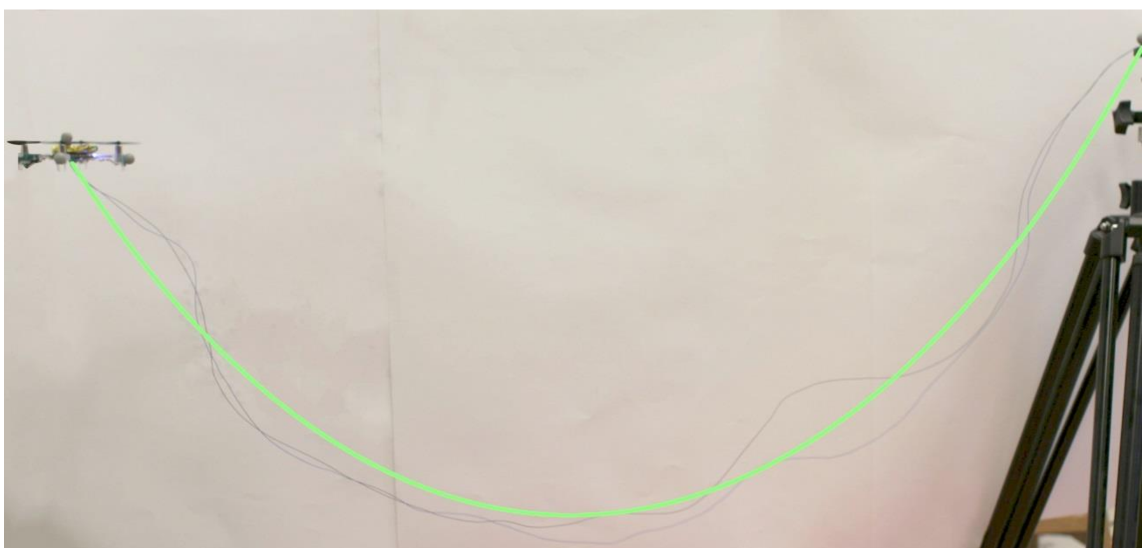
Grace Kelly (2000 dots)

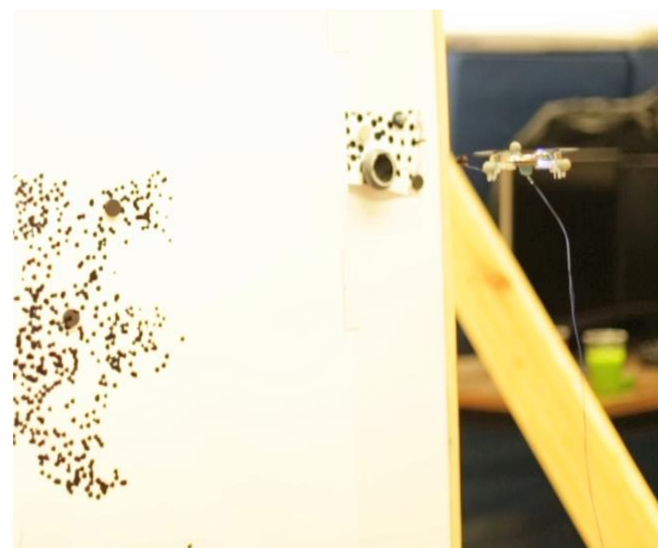
Conclusion

- Low level details involved with aerial flight control
- Stipple generation and path planning
- Dynamic error correction

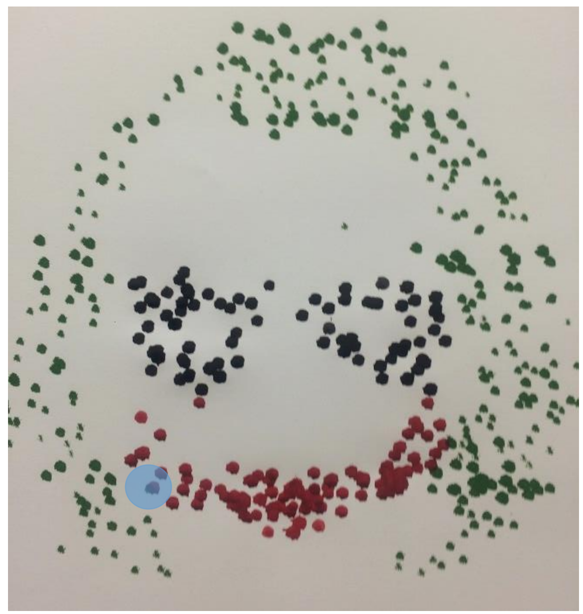
Future Work

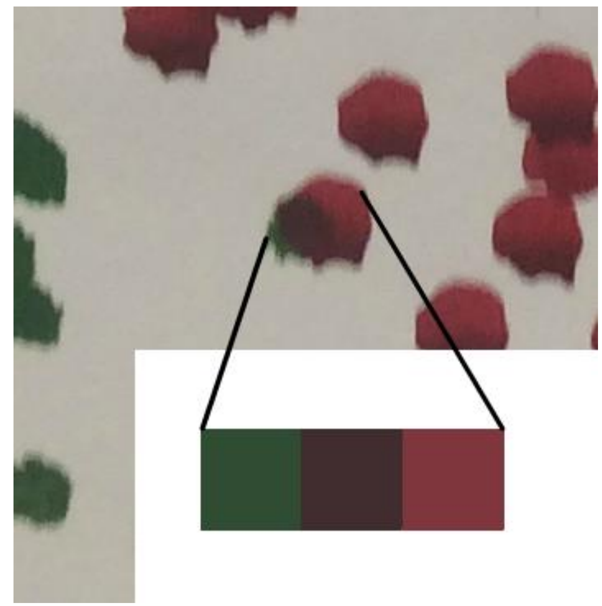
- Typical flight time on battery is less than 6 minutes
- Wire tether for continuous flight
- Model wire with catenary curve





Future Work – Colored Prints

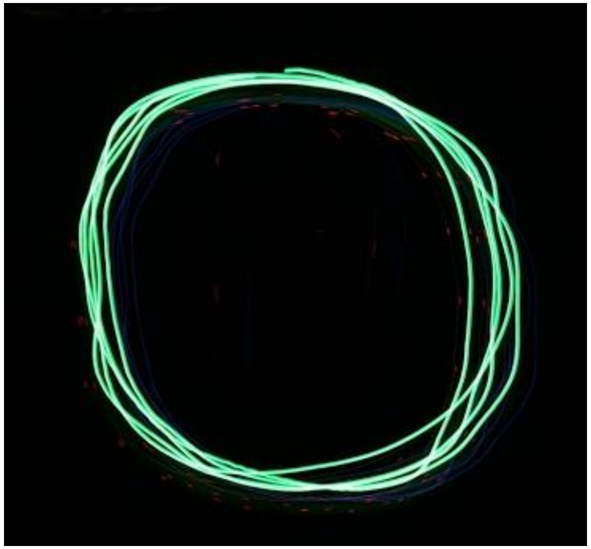


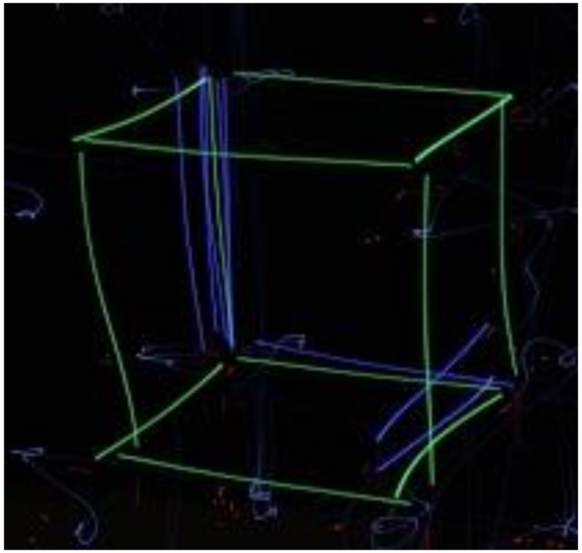


Joker (500 dots)

Future Work

- Light painting
- Multiple Quadrotor stippling





Thank you for listening