Direct Time-to-Contact Estimation for Unmanned Aerial Vehicle Landing

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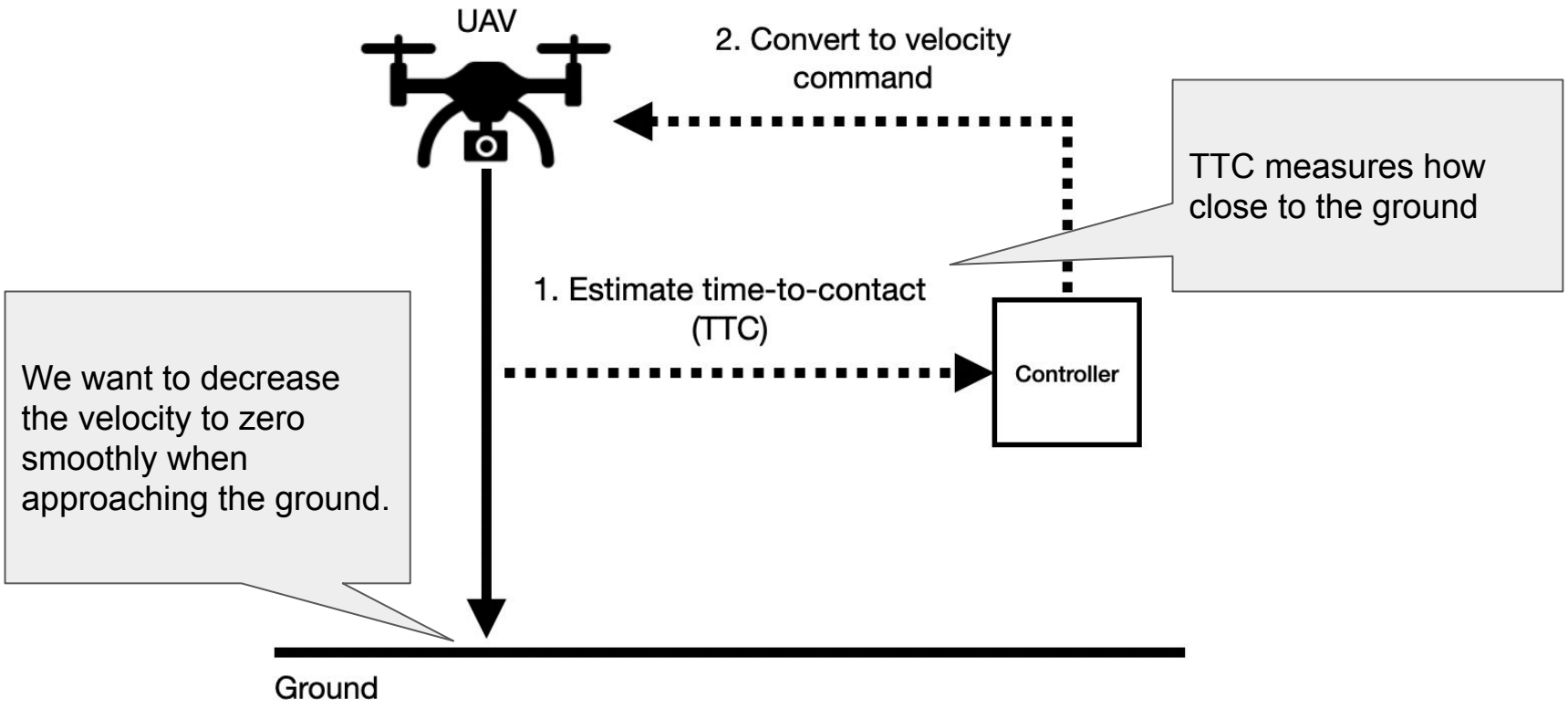
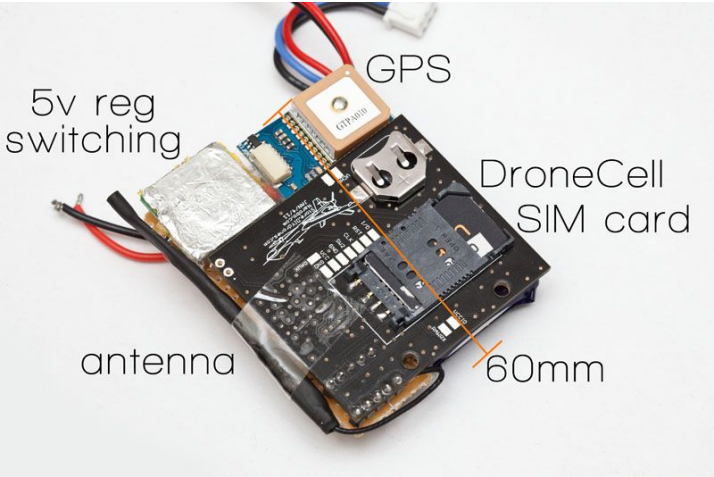
Time-to-contact (TTC) based control for UAV landing



Typical TTC-based control is unscalable

1. Expensive
2. Imprecise in indoor cases



GPS

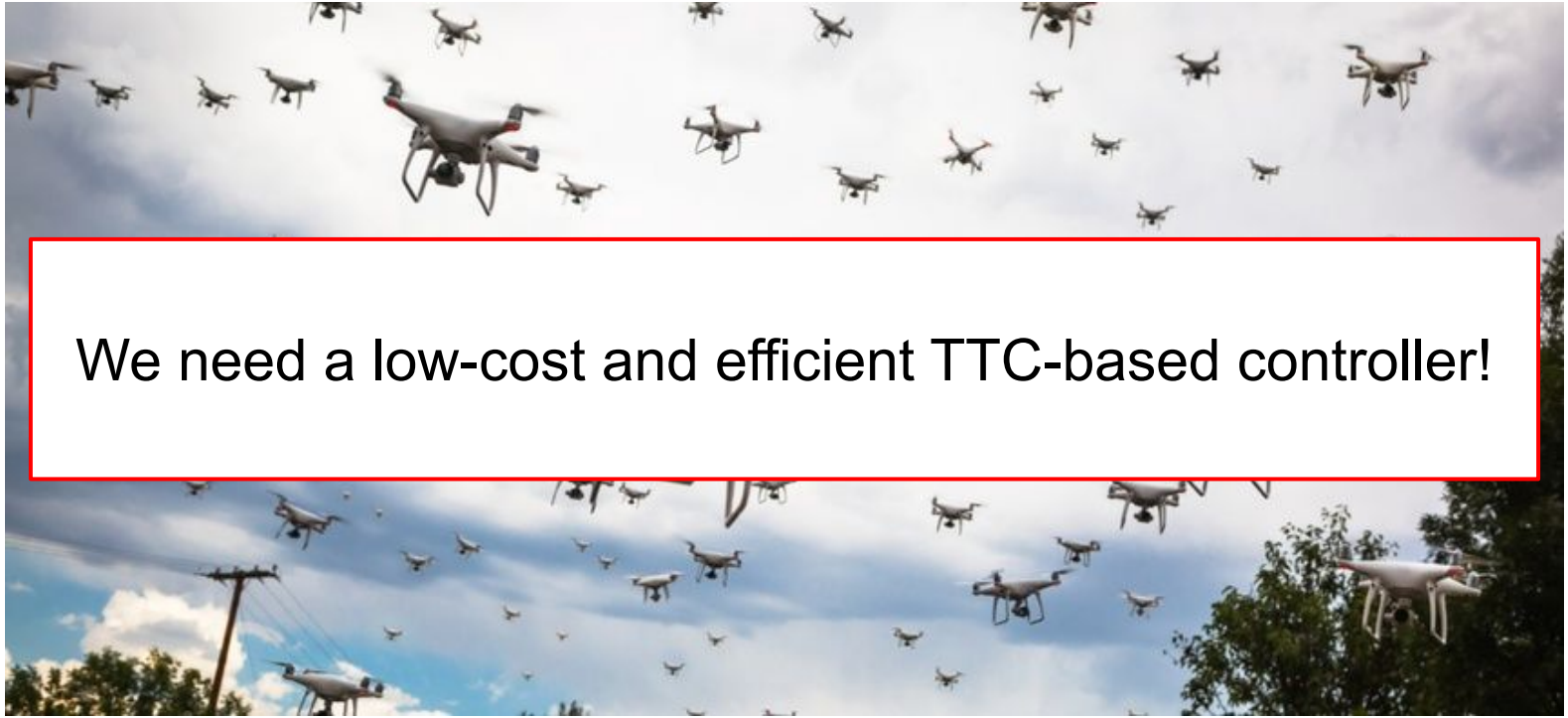
1. Need visual features
2. Costly computation

Optical flow

Typical methods cannot deploy in a scale

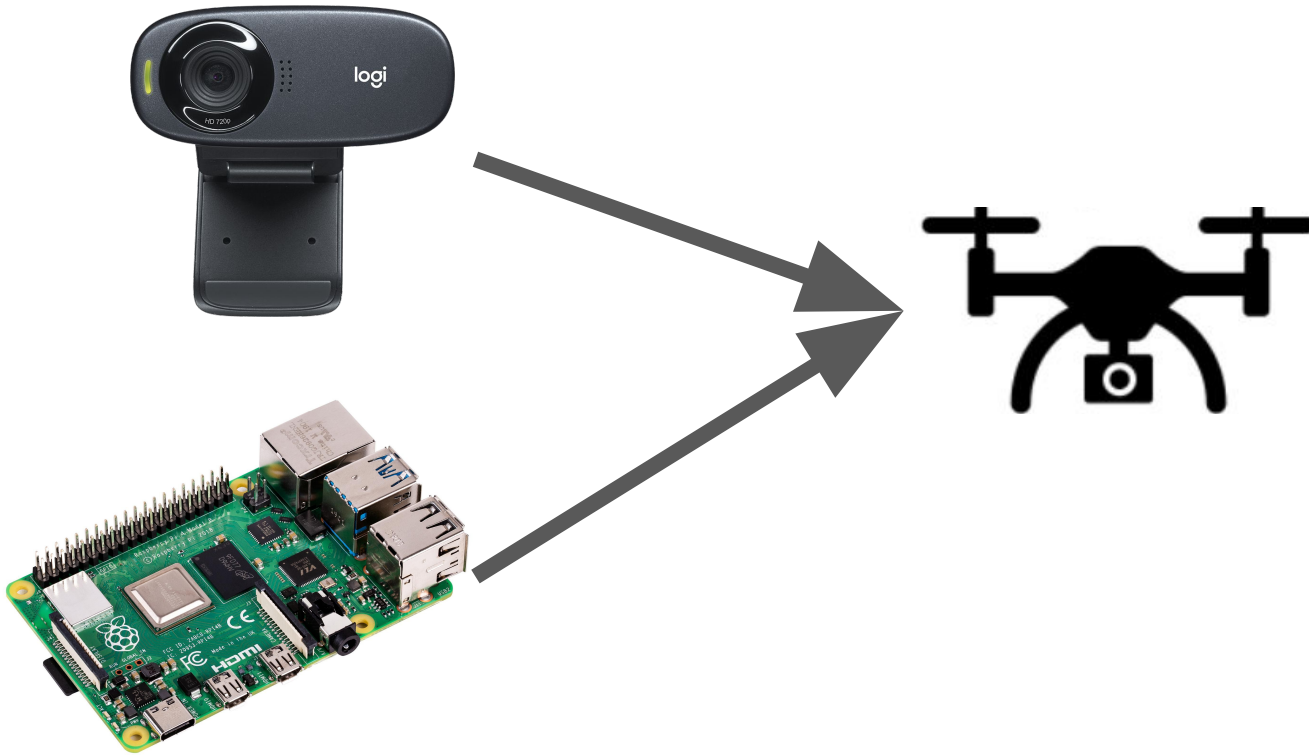
https://roboticsandautomationnews.com/

The envision of UAV is large scale deployment in smart cities



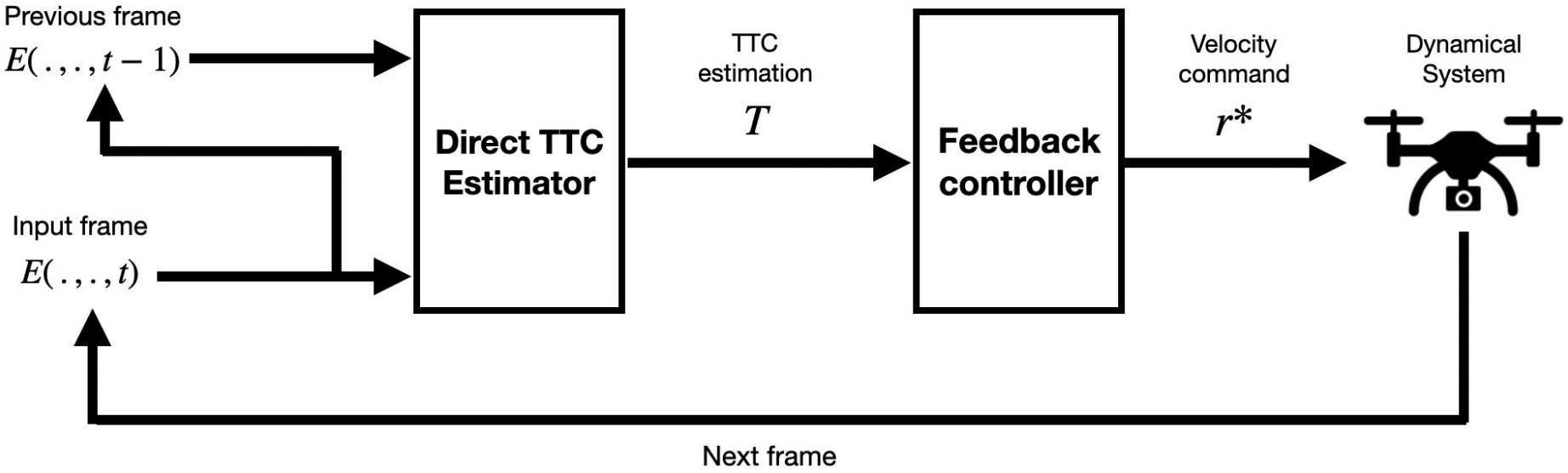
https://roboticsandautomationnews.com/

Our method only needs a monocular camera and a cheap computer



Method - overview

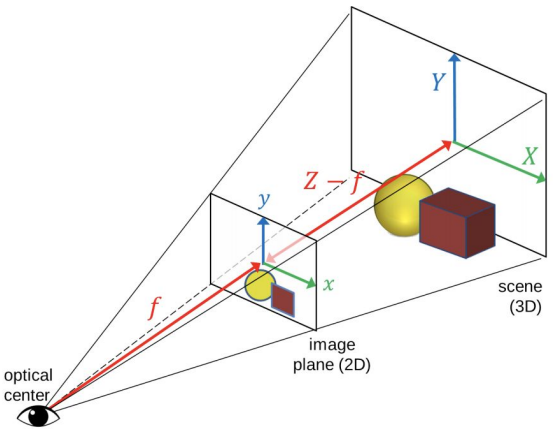
Control UAVs via direct TTC estimation [1] from **image brightness**



[1] B. K. P. Horn, Y. Fang and I. Masaki, "Time to Contact Relative to a Planar Surface," *2007 IEEE Intelligent Vehicles Symposium*, Istanbul, 2007, pp. 68-74, doi: 10.1109/IVS.2007.4290093.

Method - TTC estimatior

TTC can be connected to image brightness by **image motion**



TTC

$$T = -\frac{Z}{W}$$

Image motion

$$\frac{1}{f}\frac{dx}{dt} = \frac{1}{f}u = \frac{U}{Z} - \frac{x}{f}\frac{W}{Z}$$

$$\frac{1}{f}\frac{dy}{dt} = \frac{1}{f}v = \frac{V}{Z} - \frac{y}{f}\frac{W}{Z}$$

$$(U, V, W) = (\frac{dX}{dt}, \frac{dY}{dt}, \frac{dZ}{dt}) \quad (u, v) = (\frac{dx}{dt}, \frac{dy}{dt})$$

Method - TTC estimatior

Image motion is constrained by the **constant brightness equation (BCCE)**

$$uE_x + vE_y + E_t = 0$$

E	Image brightness
E_x	Partial derivative w.r.t. x
E_y	Partial derivative w.r.t. y
E_t	Partial derivative w.r.t. t

Method - TTC estimatior

Then, TTC can be obtained by the least-square solution of BCCE

$$u = f(\frac{U}{Z} - \frac{x}{f}\frac{W}{Z})$$
$$v = f(\frac{V}{Z} - \frac{y}{f}\frac{W}{Z})$$

Plug into

$$\min_{u,v} \sum_{x,y} (uE_x + vE_y + E_t)^2$$

Regroup

$$\min_{A,B,C} \sum_{x,y} (AE_x + BE_y + CG + E_t)^2.$$

$$G = xE_x + yE_y$$

Obtain TTC by the solved C

$$C = -\frac{W}{Z} = \frac{1}{T}$$

Method - feedback controller

Landing control can be related to TTC by **the desired landing trajectory in vertical descending**

Distance to the ground at time t: $d(t) = \frac{1}{2}at^2$ (a is the desired acceleration downward)

Relation to TTC: $$T = -\frac{Z}{W} = -\frac{d(t)}{\frac{dd(t)}{dt}} = -\frac{1}{2}\frac{at^2}{at} = -\frac{1}{2}t$$

Conversion to velocity command: $$r^* = \frac{dd(t)}{dt} = -at = -2aT$$

Method - feedback controller

Landing control can be related to TTC by **the desired landing trajectory in vertical descending**

Distance to the ground at time t:

$$d(t) = \frac{1}{2}at^2$$

(a is the desired acceleration downward)

Rel

The velocity decreases to zero along with TTC

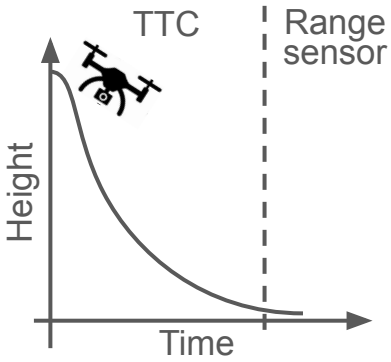
$$T = -\frac{Z}{W} = -\frac{d(t)}{\frac{dd(t)}{dt}} = -\frac{1}{2}\frac{at^2}{at} = -\frac{1}{2}t$$

Conversion to velocity command:

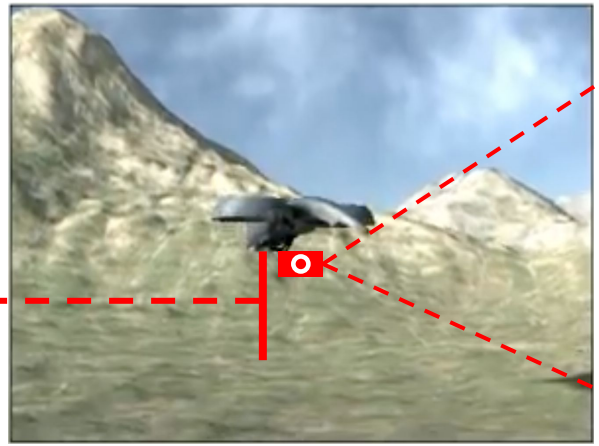
$$r^* = \frac{dd(t)}{dt} = -at = -2aT$$

Experiments setup

Sensors



Third-Person View



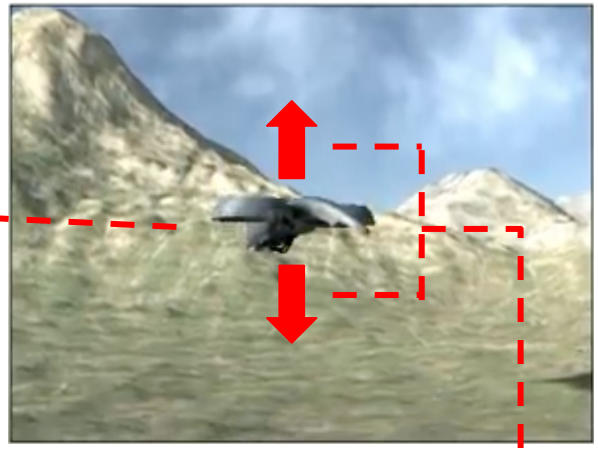
UAV's Camera View

Range sensor with operational domain <0.4m

Experiments setup

Vehicle Dynamics

Third-Person View



UAV's View

Simple Rigid Body

Velocity control along vertical axis

Experiments setup

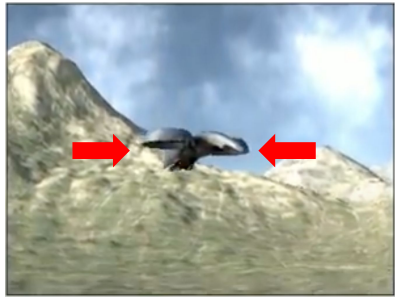
Weather Conditions

Dust Storm

Cloudy

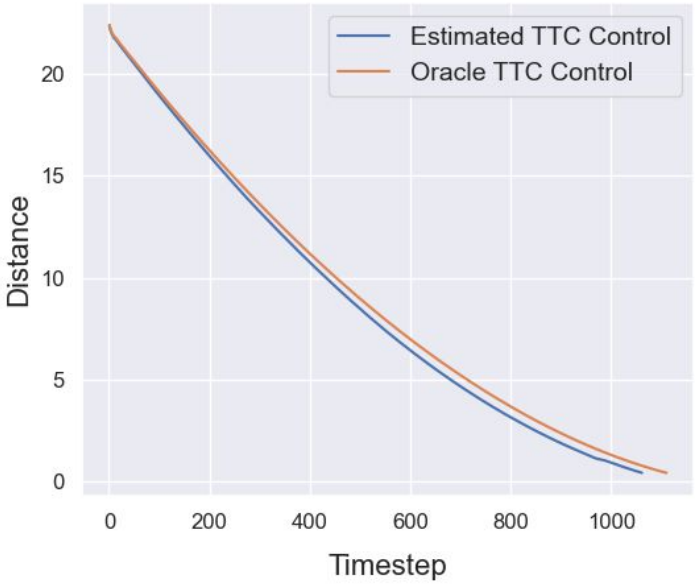
Rotational Light

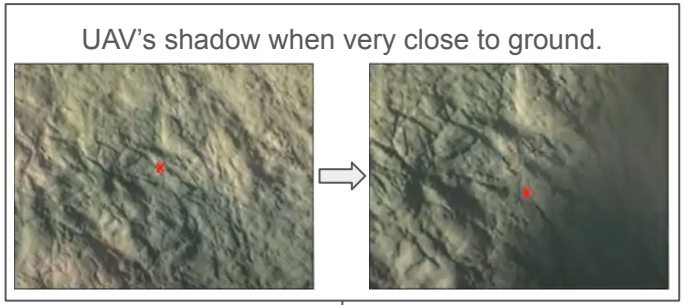
Windy

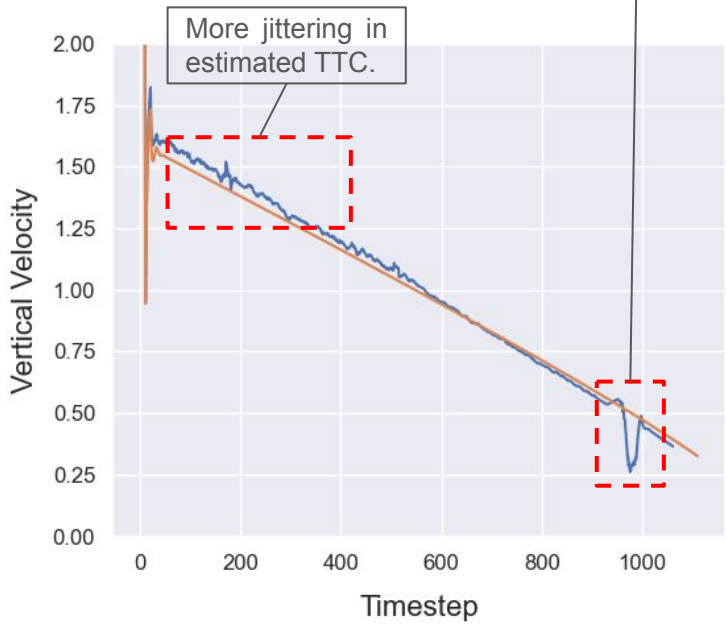


Experimental results

Control with estimated and oracle TTC.



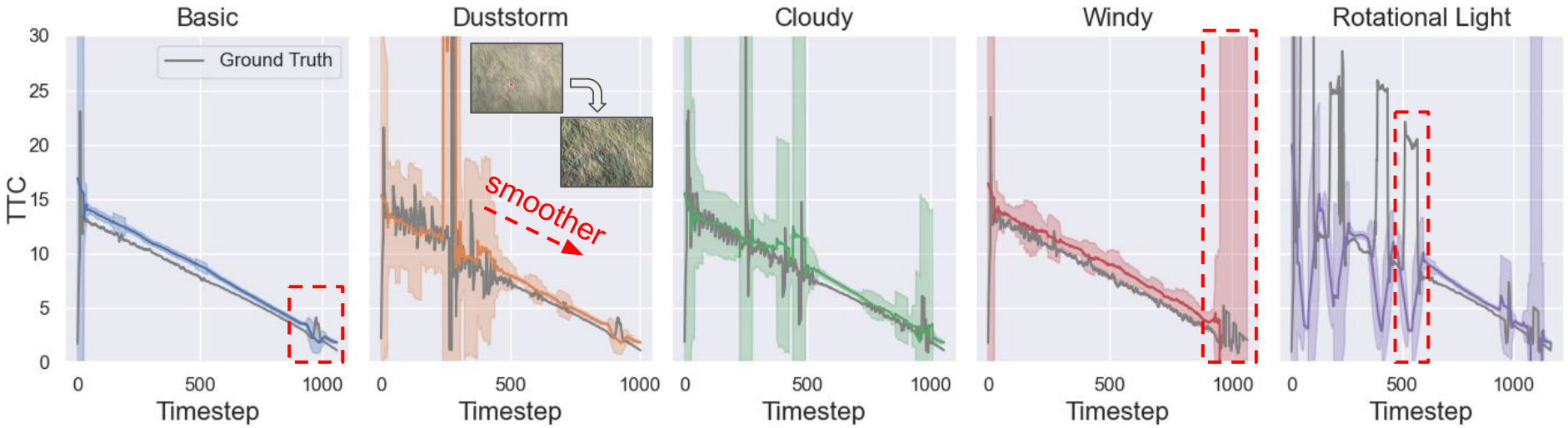




* Running mean and standard deviation is shown with window size = 50 steps.

Experimental results

TTC estimates in various weather conditions.



UAV's shadow when very close to ground.

Dust become thinner while UAV approaching the ground.

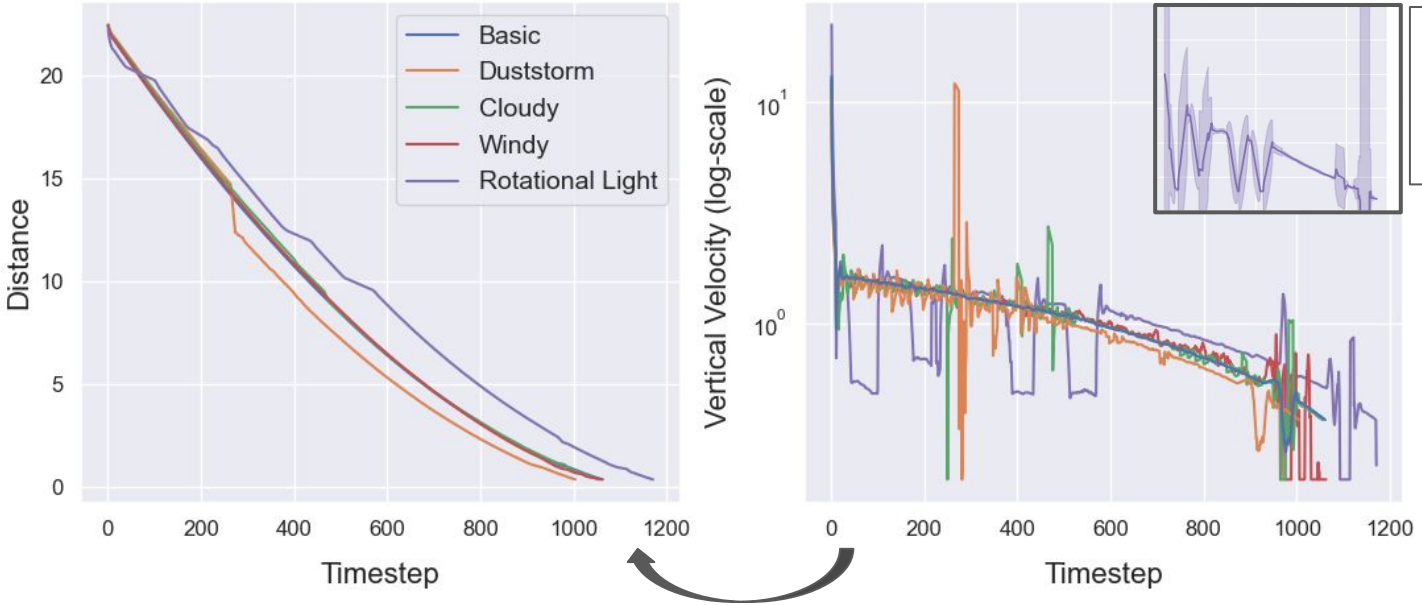
Randomly distributed variance due to random cloud motion of cloud shadow.

Horizontal translation exacerbate erroneous Et estimate due to UAV's shadow.

Small variance but large bias due to structural changes of lighting.

Experimental results

Distance to ground and vertical velocity in various weather conditions.



Much resemble TTC estimation as our velocity control is linear to TTC.

Smooth out after integration.

Slide link:
https://docs.google.com/presentation/d/1ORkHkvDeMTCSJEANafhsImeJVZhqEMRU9VSqOTVlnxw/edit?usp=sharing

BASIC

Velocity = (0.00, -1.15, 0.00)
Distance to Ground: 9.60532663
TTC = 472.468

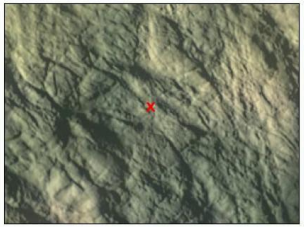
UAV's View

Third-Person View

DUST STORM

Velocity = (0.00, -0.54, 0.00)
Distance to Ground: 1.51558272
TTC = 169.755

UAV's View

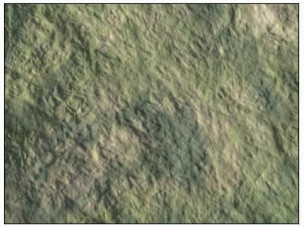


Third-Person View

WINDY

Velocity = (0.26, -1.14, -0.70)
Distance to Ground: 9.73055412
TTC = 468.371

UAV's View



Third-Person View

FREE FALL

Velocity = (0.00, -14.72, 0.00)
Distance to Ground: 11.48951047
TTC = 52.856

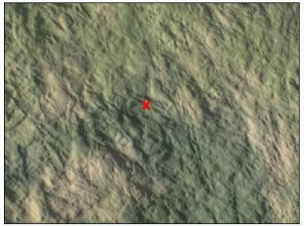
UAV's View

Third-Person View

CLOUDY

Velocity = (0.00, -0.82, 0.00)
Distance to Ground: 4.60415001
TTC = 309.813

UAV's View

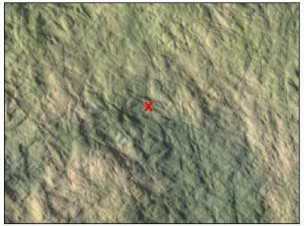


Third-Person View

ROTATIONAL LIGHT

Velocity = (0.00, -0.82, 0.00)
Distance to Ground: 4.65465098
TTC = 300.919

UAV's View



Third-Person View

Q & A