

Navigation Technologies for Micro-Aerial Vehicles

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DRDC Valcartier

November 2012



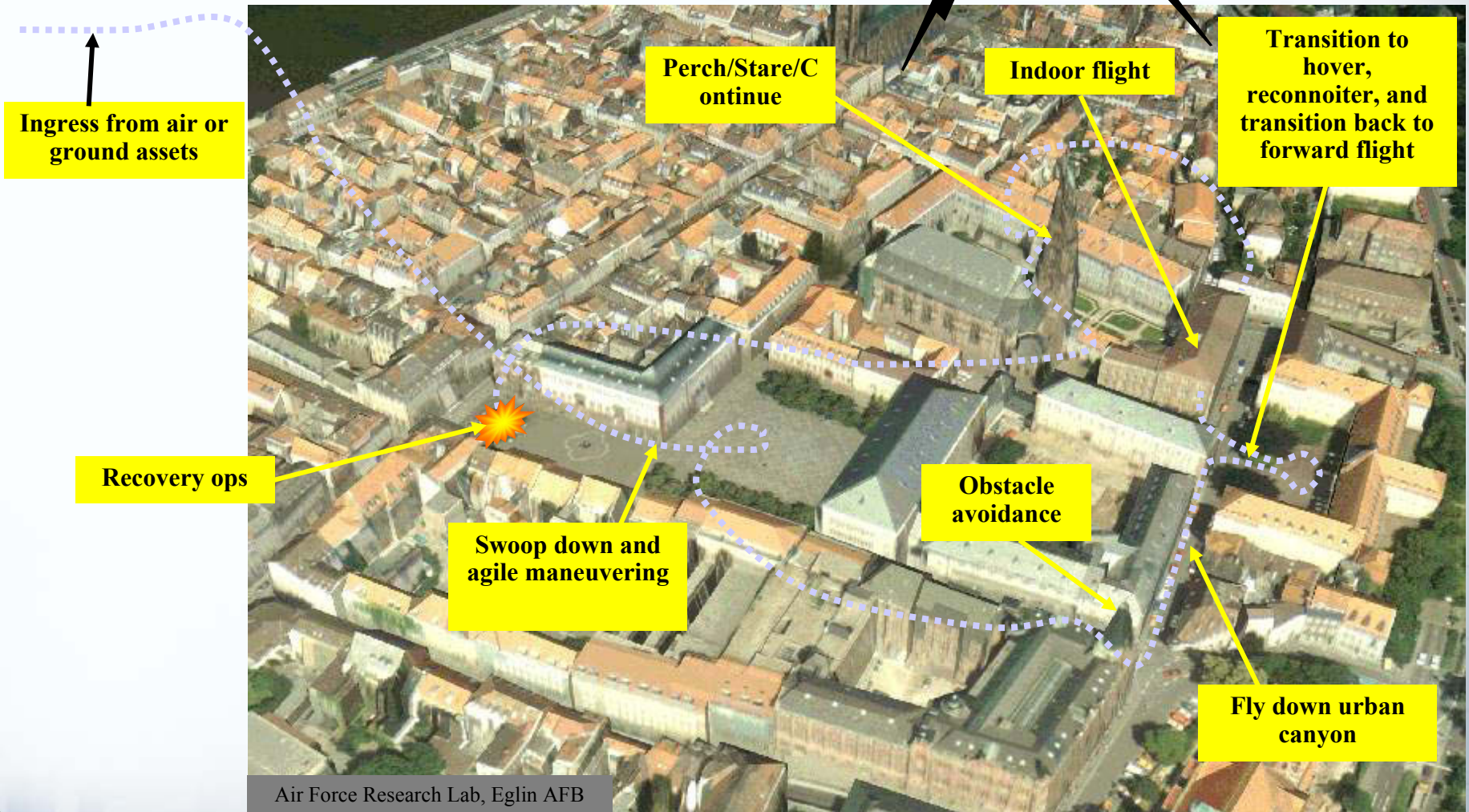
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Challenge Mission



Air Force Research Lab, Eglin AFB

Navigation is Key

- Classical approach
 - sensors
 - algorithms
- Biomimetic approach
 - sensors
 - algorithms

Classical Approach - Sensors

Inertial Measurement Unit

Crossbow ANC-1000

www.moog-crossbow.com

Microstrain 3DM-GX3

www.microstrain.com

SBG IG-500N

www.sbg-systems.com



acceleration
angular rate
magnetic field

leads to estimation of
velocity
position
heading

Classical Approach - Sensors

Infrared Time of Flight Scanner

Hokuyo UTM-30LX

www.hokuyo.aut.jp/02sensor

Sick LMS 111

www.sick.com

Velodyne HDL-32E

www.velodynelidar.com



2D range

max. range : 5 m to 30 m

3D range

max. range : 70 m

working principle:

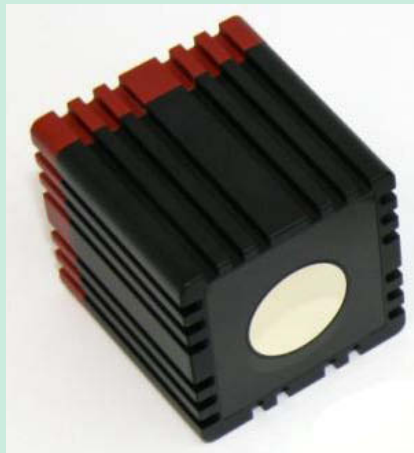
time taken for laser pulse to travel
from an illuminator to objects in the
FOV and back to the detector

Classical Approach - Sensors

Infrared Time of Flight Camera

MESA SR4000

www.mesa-imaging.ch



3D range

max. range : 5 m

working principle:
time taken for light to travel from an
active illumination source to objects in
the FOV and back to the sensor

Classical Approach - Sensors

Ultrasonic Range Finder

Devantech SRF

<http://www.robotshop.com/ca/sensors.html>

Maxbotix XL-MaxSonar

www.maxbotix.com

Parallax PING

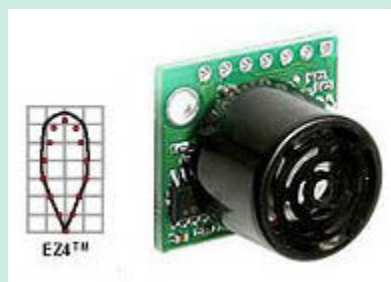
www.parallax.com

1D range

max. range : 2 cm to 10 m

working principle:

time taken for sound to travel from an active transducer to objects in the beam width and back to the detector



Classical Approach - Algorithms

Reactive Obstacle Avoidance

Instantaneous mapping of environment and path generation.

Durham et al. (2008), IROS, 1-9
 Minguez & Montano (2004), IEEE Trans Robotics and Auto., Vol. 20, 45-59
 Simmons (1996), Proc IEEE Intl Conf Robotics and Auto, 3375-3382
 Ulrich & Borenstein (1998), IEEE Intl Conf Robotics and Auto, 1572-1577

Simultaneous Localization and Mapping

Incremental build of a spatially consistent map with concurrent computation of location within the map to allow path planning.

Celik et al. (2008), AIAA GNC Conf, AIAA 2008-6670
 Grisetti et al. (2007), Robotics and Autonomous Syst, Vol. 55, 30-38

Structure from Motion

Reconstruction of vehicle pose relative to the 3D environment through feature-point tracking in successive images.

Prazenica et al. (2007), AIAA GNC Conf, AIAA 2007-6830
 Watkins (2007), PhD Thesis, U Florida

Biomimetic Approach - Sensors

Vision

monocular camera

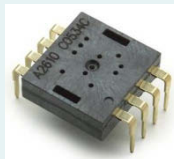
Centeye

www.centeye.com



optical mouse ADNS-2610

<https://www.sparkfun.com/products/10105>



PrimeSense

www.primesense.com



array of CCD or CMOS detectors

compound eye composed of elementary motion detectors

simple elementary motion detector

3D scanner using structured light

Hierarchy of Technologies for Vision-based Micro-Aerial Vehicles

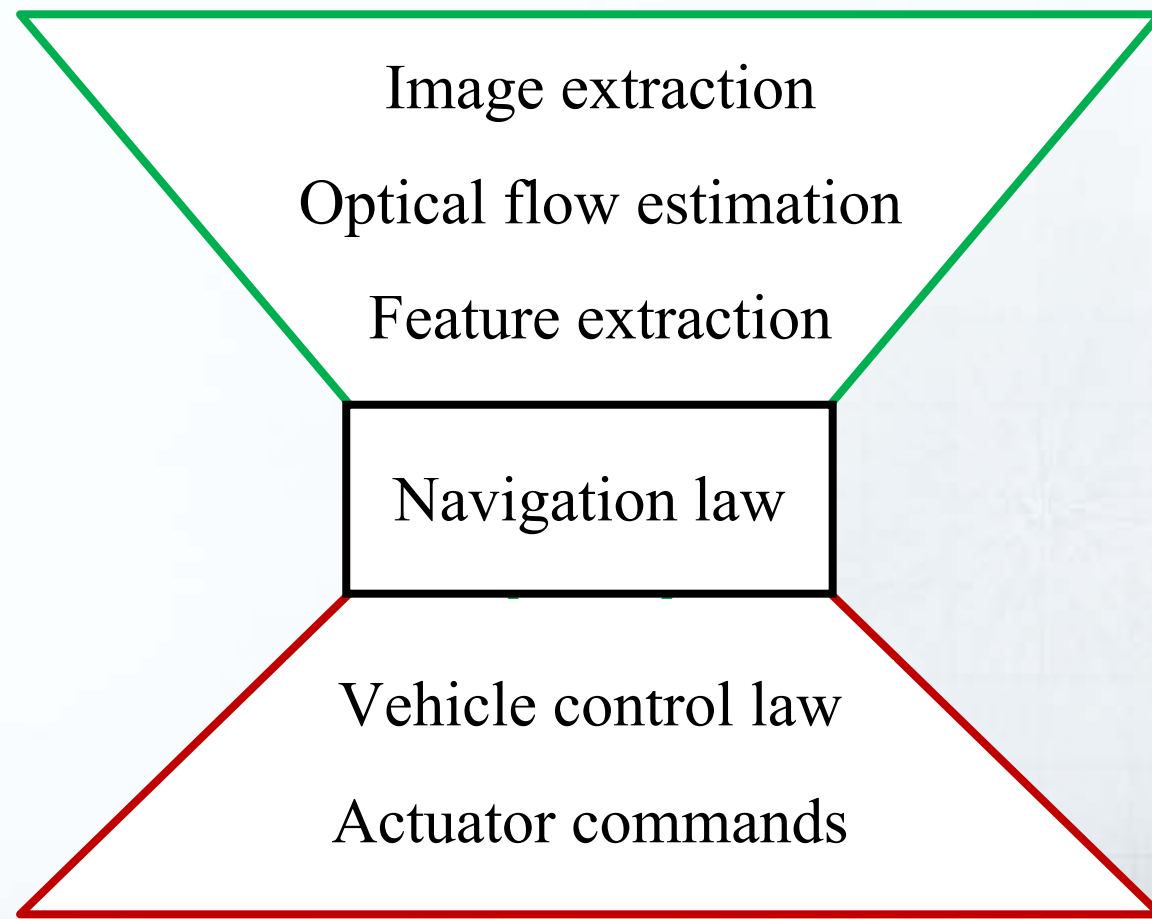
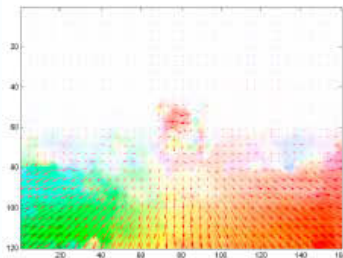
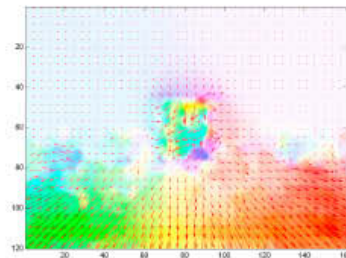


Image Extraction

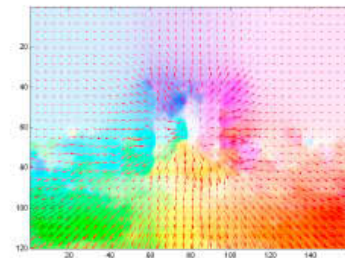
- 160x120 pixels, 10 fps, computation time = 0.23 s



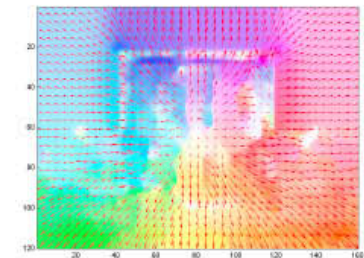
(a) Position # 1



(b) Position # 2

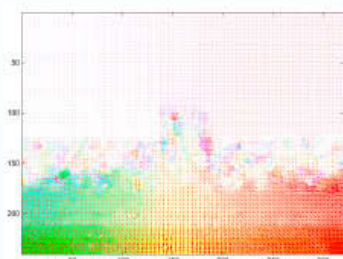


(c) Position # 3

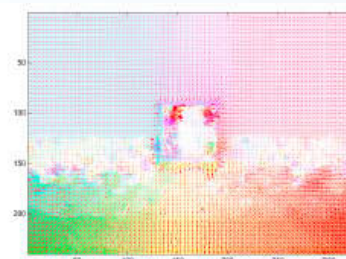


(d) Position # 4

- 320x240 pixels, 30 fps, computation time = 2.26 s



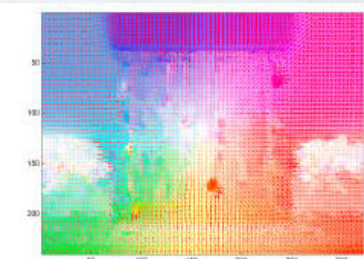
(a) Position # 1



(b) Position # 2



(c) Position # 3



(d) Position # 4

Optical Flow Estimation

- Optical flow due to general camera motion

Coombs, D. et al. (1998), IEEE Trans Robotics and Automation, Vol. 14, 49-58.

$$\begin{aligned} u &= (1/Z)(-T_x + xT_z) + [xy\omega_x - (1 + x^2)\omega_y + y\omega_z] \\ v &= (1/Z)(-T_y + yT_z) + [(1 + y^2)\omega_x - xy\omega_y - x\omega_z] \end{aligned}$$

- Optical flow based on image pixel brightness

$$\frac{\partial I}{\partial x} V_x + \frac{\partial I}{\partial y} V_y + \frac{\partial I}{\partial t} = 0$$

Optical Flow Estimation

- Horn & Schunck – global smoothness constraint

Horn and Schunck (1981), Artificial Intelligence, Vol. 17, 185-203.

$$E = \iint \left[(I_x u + I_y v + I_t)^2 + \alpha^2 (\|\nabla u\|^2 + \|\nabla v\|^2) \right] dx dy dt$$

- Liu (Lucas & Kanada) – local smoothness constraint

Lucas and Kanade (1981), Proc. Of DARPA Image Understanding Workshop, 121-130.

Liu (2009), PhD Thesis, MIT

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} \sum_t I_x(q_t)^2 & \sum_t I_x(q_t) I_y(q_t) \\ \sum_t I_x(q_t) I_y(q_t) & \sum_t I_y(q_t)^2 \end{bmatrix}^{-1} \begin{bmatrix} -\sum_t I_x(q_t) I_t(q_t) \\ -\sum_t I_y(q_t) I_t(q_t) \end{bmatrix}$$

- Other algorithms

vision.middlebury.edu/flow/eval

Feature Extraction – Time to Contact

- TTC based on flow divergence

Coombs, D. et al. (1998), IEEE Trans Robotics and Automation, Vol. 14, 49-58.

$$\frac{\partial u}{\partial x} = \rho T_z + y\omega_x - 2x\omega_y$$

$$\frac{\partial v}{\partial y} = \rho T_z + 2y\omega_x - x\omega_y$$

$$T_c = \frac{2}{\nabla(u, v)} \quad \text{at } (x, y) = (0, 0)$$

- TTC at pixel location (x, y)

Low & Wyeth (2005), Australasian Conf Robotics and Automation, 1-10.

$$T_c = \frac{\cos\phi \times \sin\phi}{\dot{\phi}}$$

$$\dot{\phi} = u \cos \theta + v \sin \theta$$

ϕ = spherical angle between optical axis and vector from focal point to pixel on image plane

θ = polar angle on image plane

Navigation Law

- Global TTC

$$T_{cbalance} = \sum_{i=0}^{n/2} \sum_{j=0}^m T_c(i, j) - \sum_{i=n/2}^n \sum_{j=0}^m T_c(i, j)$$

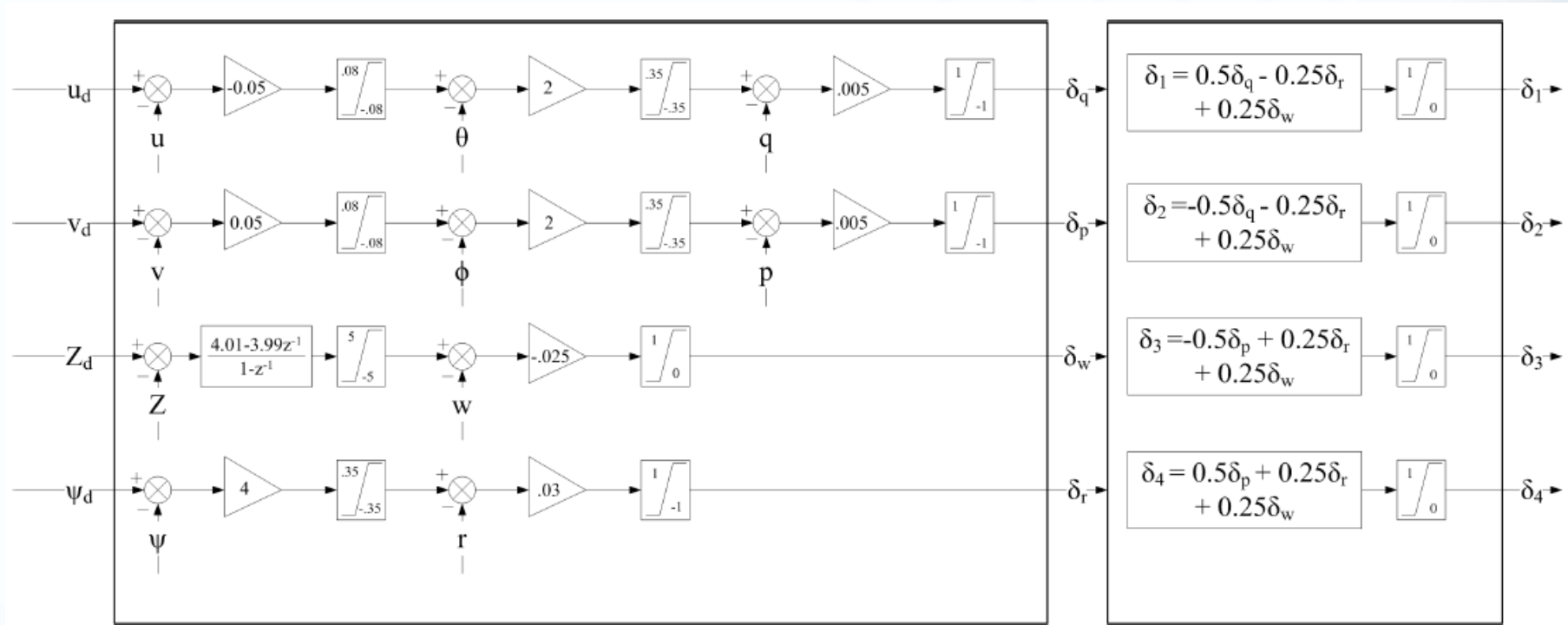
$$T_c = K_{scaling} \sum_{i=0}^n \sum_{j=0}^m T_c(i, j)$$

- Heading and speed commands

$$\psi_{cmd} = \left(-\frac{\pi}{36} * (T_c)^2 + \frac{\pi}{4} \right) * \text{sign}(T_{cbalance})$$

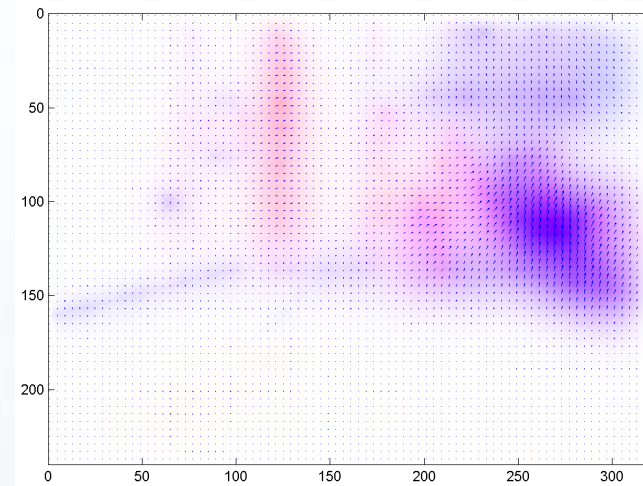
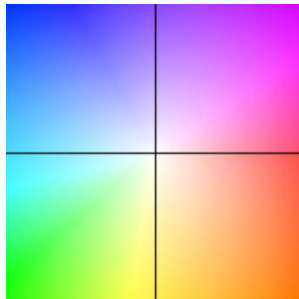
$$v_{cmd} = \left(-\frac{1}{18} * (T_c)^2 + \frac{1}{2} \right) * \text{sign}(T_{cbalance})$$

Quadrotor Control Law

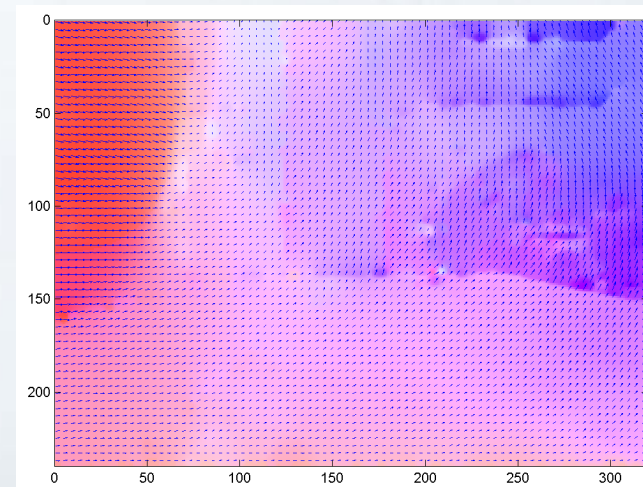


Simplified control law for simulation study only.

Comparison of Optical Flow Estimation Methods



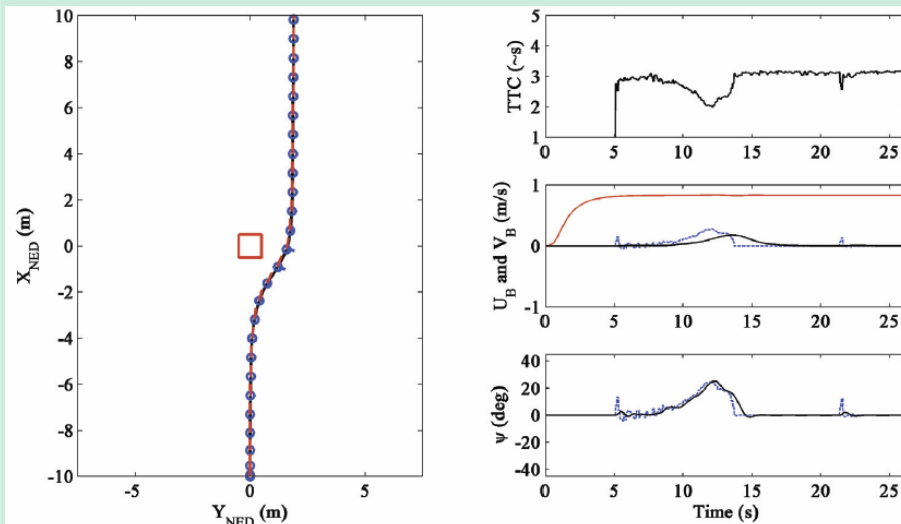
H&S



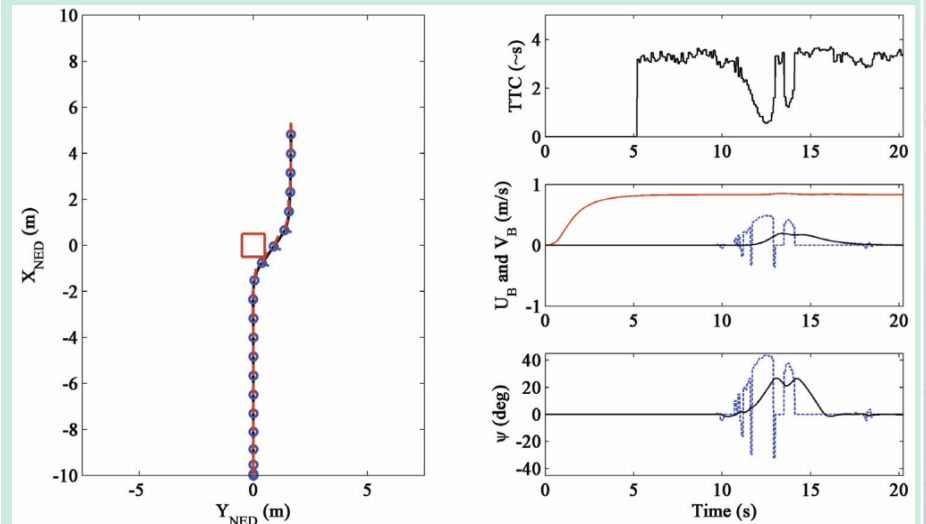
Liu

Obstacle Avoidance Simulation – 1 Obstacle

H&S optical flow

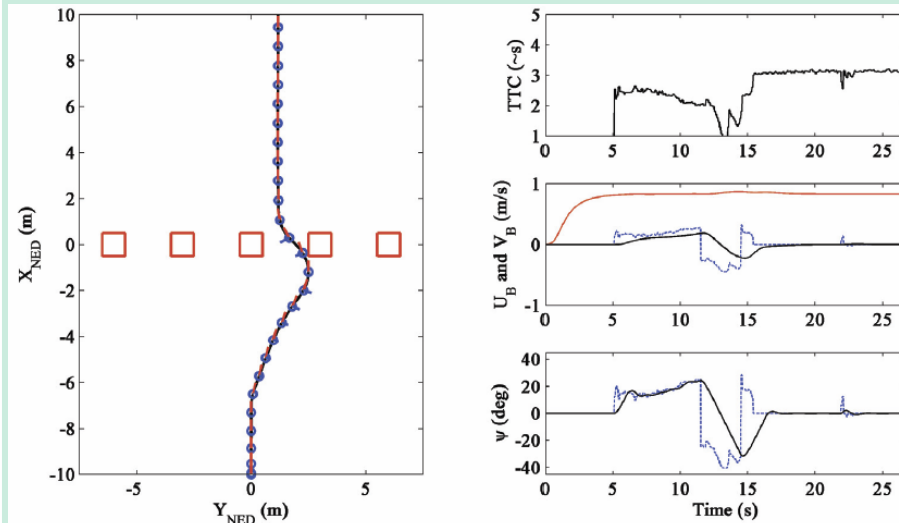


Liu optical flow

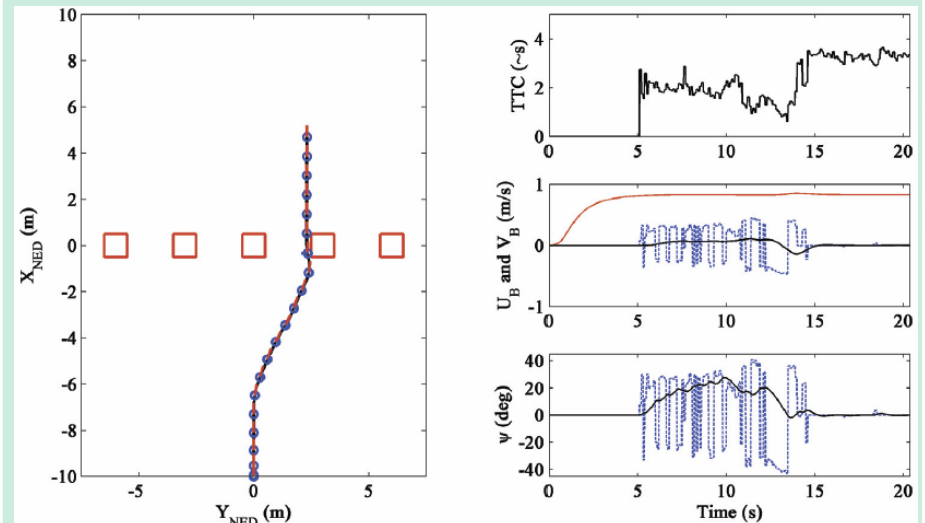


Obstacle Avoidance Simulation – 5 Obstacles

H&S optical flow



Liu optical flow



Summary

- Classical navigation approach comprised of sensors that measure distances to objects and algorithms that exploit absolute distance measurements to compute navigation commands.
- Biomimetic approach comprised of sensors that pixelate objects in an image plane and algorithms that exploit pixel movement to deduce object location in order to compute navigation commands.
- As the size of a micro-aerial vehicle reduces, the viability of using classical navigation methods decreases unless classical navigation sensors have a dramatic decrease in size, weight and power consumption.
- Vision-based navigation methods may offer an avenue to miniaturize the navigation sub-system on micro-aerial vehicles. However, further development to increase the robustness of optical flow-based navigation algorithms is required.

Other Interesting References

Ahrens (2009), "Vision-based Guidance and Control of a Hovering Vehicle in Unknown, GPS-denied Environments", Proc IEEE Intl Conf Robotics and Auto, 2643-2648.

Beyeler et al. (2007), "3D Vision-based Navigation for Indoor Flyers", IEEE Intl Conf Robotics and Auto (ICRA).

Floreano et al. (2009), Flying Insects and Robots, Springer.

Lewinger et al. (2006), "Obstacle Avoidance Behavior for Biologically-Inspired Mobile Robot using Binaural Ultrasonic Sensors", IEEE/RSJ Intl Conf on Intell Robots and Syst, 5769-5774.

Minguez et al. (2004), "Divide and Conquer Strategy based on Situations to Achieve Reactive Collision Avoidance in Troublesome Environments", IEEE Intl Conf Robotics and Auto, Vol. 4, 3855-3862.

Moeckel and Liu (2010), Motion Detection Chips for Robotic Platforms, Springer.

Zuffrey and Floreano (2006), "Fly-Inspired Visual Steering of an Ultralight Indoor Aircraft", IEEE Trans on Robotics, Vol. 22, 137-146.

Zuffrey (2008), "Bio-Inspired Flying Robots: Experimental Synthesis of Autonomous Indoor Flyers", Chap. 3, EPFL Press.