Design and Implementation of a Mini Quadrotor Control System in GPS Denied Environments

Chang Liu
cl21g11@soton.ac.uk
http://www.southampton.ac.uk/engineering/postgraduate/research_students/cl21g11.page

Supervisors:
Dr Stephen Prior
Prof James Scanlan
University of Southampton
New Boldrewood Campus for Engineering Faculty

http://virtualopen.day.southampton.ac.uk/boldrewood-campus/boldrewood-plaza
Autonomous System Lab
University of Southampton

- **HALO**: MoD Grand Challenge 2008 entry, HALO was the highest scoring system in the recent DARPA UAVForge Challenge

- **SULSA**: World first fully 3D printed UAV

- **2SEAS**: World’s first rapid prototyped unmanned aircraft under 20 kg MTOM

- Eurobot World Final, Nano UAS

[http://blog.soton.ac.uk/robotics/]
External Localizer
Why GPS-denied Environment?

- In Military: GPS jam, no GPS service.
Why Monocular Camera?

- Small & Light Weight.
- Lower Power Consumption. (Passive)
- Low Price. (£50)
- Unlimited Range with Computation.
- Adjustable Field of View.
- Accuracy proportional to visual scale
# Why Monocular Camera?

<table>
<thead>
<tr>
<th>Solution Type</th>
<th>Expandable</th>
<th>Mass</th>
<th>Power</th>
<th>Accuracy</th>
<th>FOV</th>
<th>Price</th>
<th>Information Captured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Image Pixels</td>
</tr>
<tr>
<td>External Localization (Vicon Bonita 3)</td>
<td>No</td>
<td>0.226 kg</td>
<td>15 W</td>
<td>0.5 mm</td>
<td>$82^\circ \times 66^\circ$</td>
<td>around £20,000</td>
<td>Yes</td>
</tr>
<tr>
<td>Visual Land Mark</td>
<td>No</td>
<td>around 0.03 kg</td>
<td>around 0.3 W</td>
<td>Depends on Image Resolution</td>
<td>Adjustable</td>
<td>around £50</td>
<td>Yes</td>
</tr>
<tr>
<td>Automotive RADAR</td>
<td>Yes</td>
<td>&lt; 0.5 kg</td>
<td>3.7 W-12 W</td>
<td>0.3 m</td>
<td>$45^\circ \times 5^\circ$</td>
<td>around £700</td>
<td>No</td>
</tr>
<tr>
<td>SAR</td>
<td>Yes</td>
<td>&gt; 2 kg</td>
<td>&gt; 15 W</td>
<td>1 m</td>
<td>$5^\circ \times 5^\circ$</td>
<td>around £60,000</td>
<td>No</td>
</tr>
<tr>
<td>Laser Scanner</td>
<td>Yes</td>
<td>0.2 kg-0.8 kg</td>
<td>3 W-10 W</td>
<td>20 mm</td>
<td>180$^\circ$ to 270$^\circ$ 2D plane</td>
<td>around £4,000</td>
<td>No</td>
</tr>
<tr>
<td>Flash LIDAR</td>
<td>Yes</td>
<td>0.05 kg-1 kg</td>
<td>2.5 W-15 W</td>
<td>Over 20 mm</td>
<td>$60^\circ \times 45^\circ$</td>
<td>£50-£2,000</td>
<td>No</td>
</tr>
<tr>
<td>Stereo Camera</td>
<td>Yes</td>
<td>around 0.07 kg</td>
<td>around 0.7 W</td>
<td>Depends on Image Resolution</td>
<td>Adjustable</td>
<td>around £100 (two cameras)</td>
<td>Yes</td>
</tr>
<tr>
<td>Monocular Camera</td>
<td>Yes</td>
<td>around 0.03 kg</td>
<td>around 0.3 W</td>
<td>Depends on Image Resolution</td>
<td>Adjustable</td>
<td>around £50</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Problem Statement
Main Hardware (COTS): Autopilot

- Arm Cortex-M4
- Servo Controller
- FreelIMU
- Xbee Radio
Main Hardware (COTS): Cameras and Onboard Computer

- Optical Flow Camera with ultrasonic
- UEYE Global Shutter Camera
- Quad-core Single Board Computer
Main Hardware (COTS): Interactions

Main Controller

Servo Controller

ESC

Velocity and Altitude Sensor

Interface Arduino

Global Shutter Camera

Additional Vision Computer

USB

UART1

UART2

UART3

400 KHz I²C

100 KHz I²C

333 Hz PWMs

Manual RC controller

RC receiver

XBee

PC Ground Station
Controller Algorithm Overview

\[
\begin{align*}
\dot{x}, \dot{y} &\rightarrow \text{Velocity Controller} \\
\phi^*, \theta^* &\rightarrow \text{Attitude Controller} \\
\psi^* &\rightarrow \text{Quadcopter Dynamics} \\
T^*_\text{total} &\rightarrow \text{Altitude Controller} \\
\dot{z}^* &\rightarrow \text{Altitude Controller} \\
z, \Theta &\rightarrow \text{Quadcopter Dynamics} \\
\dot{x}, \dot{y}, \psi &\rightarrow \text{Velocity Controller}
\end{align*}
\]
Quadcopter Dynamics

- **Velocity Controller**: Inputs $\dot{x}^*, \dot{y}^*$
- **Attitude Controller**: Inputs $\psi^*, \phi^*, \theta^*$
- **Altitude Controller**: Inputs $z^*$
- **Quadcopter Dynamics**: Outputs $\dot{x}, \dot{y}, \psi$, $z, \Theta$, $T^*$, $\delta^*$

Connections:
- $\dot{x}^*, \dot{y}^* \rightarrow$ Velocity Controller
- $\psi^*, \phi^*, \theta^* \rightarrow$ Attitude Controller
- $z^* \rightarrow$ Altitude Controller
- $T^* \rightarrow$ Quadcopter Dynamics
- $\Theta \rightarrow$ Quadcopter Dynamics
- $\dot{x}, \dot{y}, \psi \rightarrow$ Quadcopter Dynamics
Quadcopter Dynamics
1. Rotor Dynamics

\[ T = c_T (\delta - c_o)^2, \]
\[ Q = c_Q T, \]
Quadcopter Dynamics

2. Forces and Moments Generation

Total force

\[ F = F_{\text{gravity}} + F_{\text{thrust}} \]

\[ F_{\text{thrust}} = R \frac{w_b}{b} \begin{pmatrix} 0 \\ 0 \\ -(T_1 + T_2 + T_3 + T_4) \end{pmatrix}, \]

\[ F_{\text{gravity}} = \begin{pmatrix} 0 \\ 0 \\ mg \end{pmatrix}, \]

Total Moment

\[ M = B C T, \]

\[ B = \begin{bmatrix} \frac{\sqrt{2}}{2} l & 0 & 0 \\ 0 & \frac{\sqrt{2}}{2} l & 0 \\ 0 & 0 & c_Q \end{bmatrix}, \]

\[ C = \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & 1 & -1 & 1 \end{bmatrix}, \]

\[ T = (T_1, T_2, T_3, T_4)^T, \]
Quadcopter Dynamics

3. Rigid Body Dynamics

Newton- Euler formalism

\[
m \ddot{P}_w = F_w, \\
J \ddot{\Theta} + \dot{\Theta} \times (J \dot{\Theta}) = M,
\]

\[
J = \begin{bmatrix}
J_X & 0 & 0 \\
0 & J_Y & 0 \\
0 & 0 & J_Z \\
\end{bmatrix},
\]

Forces and Moments Generation

Rigid Body Dynamics

bifilar pendulum theory

\[
J = \frac{mgT^2b^2}{4\pi^2L},
\]
Attitude Controller

Velocity Controller

Attitude Controller

Quadcopter Dynamics

Altitude Controller

$x^*, \dot{x}^*$

$\psi^*$

$\phi^*, \theta^*$

$T^*_{total}$

$z^*$

$z, \Theta$

$\dot{x}, \dot{y}, \psi$

$\delta^*$
Attitude Controller

1. PID Controller

\[ e_\theta = \Theta^* - \Theta = \begin{pmatrix} \Delta\phi \\ \Delta\theta \\ \Delta\psi \end{pmatrix}, \]

\[ u_\theta = K_p e_\theta + K_i \int e_\theta \, dt + K_d \dot{e}_\theta, \]

2. Quadcopter Dynamics Inversion

1. Moment Inversion

\[ M^* = 4B u_\theta, \]

\[ T^* = \begin{bmatrix} 1_{4 \times 1} & C^T \end{bmatrix} \begin{bmatrix} T_{\text{total}}^*/4 \end{bmatrix}, \]

2. Rotor Dynamics Inversion

\[ \delta^*_n = \sqrt{\frac{T_n^*}{c_T}} + c_o. \]
Altitude Controller
Altitude Controller

1. PID Controller

\[ e_z = z^* - z. \]
\[ u_z = K_{pz} e_z + K_{iz} \int e_z \, dt + K_{dz} e_z', \]

2. Rigid Body Dynamics Inversion

\[ \ddot{z}^* = \frac{u_z}{m}. \]
\[ T_{total}^* = \frac{mg - u_z}{c_\phi c_\theta}. \]
Velocity Controller

\[ \dot{x}^*, \dot{y}^* \rightarrow \text{Velocity Controller} \]

\[ \psi^* \rightarrow \text{Attitude Controller} \]

\[ \phi^*, \theta^* \rightarrow \text{Attitude Controller} \]

\[ T_{total}^* \rightarrow \text{Altitude Controller} \]

\[ z^* \rightarrow \text{Altitude Controller} \]

\[ \dot{x}, \dot{y}, \psi \rightarrow \text{Quadcopter Dynamics} \]

\[ \delta^* \rightarrow \text{Quadcopter Dynamics} \]

\[ z, \Theta \rightarrow \text{Altitude Controller} \]
Velocity Controller

1. PID Controller

\[ e_v = v^* - v. \]
\[ u_v = K_{pu}e_v + K_{iv} \int e_v \, dt + K_{dv}e'_v, \]

2. Rigid Body Dynamics Inversion

\[ \dot{v}^* = \frac{u_v}{m}. \]
\[ \phi^* = \sin^{-1} \left( \frac{u_{vy}}{\sqrt{1 - u_{vx}^2}} \right), \]
\[ \theta^* = -\sin^{-1} (u_{vx}). \]
Test Result
SLAM Third Party Algorithm

Natural Features being tracked in 3D map (re-projected back in video)

Natural Features being reconstructed in 3D map

6 DOF Quadrotor State Estimation

Historical Path
Future Work

- Sensor fusion algorithm.
- Position controller development.
- Robustness improvement (failure handling)
- Maybe sense and avoid.
Conclusion

- We have shown the design and implementation detail of a quadrotor system in GPS-denied environment.
- Based on the flight test data, we have shown the effectiveness of optical flow sensor for the purpose of controlling the vehicle horizontal velocity and altitude.
- Future work has been proposed briefly.
Thank you for listening – Questions?