FORMATION FLYING OF 3 MAVS FROM DESIGN TO FLIGHT TESTING

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The potential of the individual micro aerial vehicles can be increased by collectively using a group of micro aerial vehicles which has greater adaptability and flexibility.

Applications:

- Large area surveillance and reconnaissance
- 3D aerial imaging
- Border patrolling
- Wildlife conservation
- Exploration mapping

Battle space management scenario illustrating distributed command and control between heterogeneous air and ground assets.

Figure courtesy of DARPA.
Objective

Problem Definition

Pushpak : Mini UAV

Formation Controller Description (SDC)

SILS/PILS of formation controller

Formation Flight procedure

Leader-Follower flight results
To design and simulate a formation control algorithm to fly three MAVs in triangle pattern and further test the control in real flight on three MAVs.

In future this formation control can be applied to practical problems like large area precision farming, wild life poaching activities, border patrolling.
Problem Definition

- Formation of 3 MAVs in triangle pattern
- One Leader-Two Follower MAVs
- Control separation and deviation angle among Leader and Followers

- Wireless transmission among MAVs: Leader sends its GPS Location, velocity And heading to Followers.
- All MAVs send their location to Ground Control Station
<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using multiple Xbee’s and RC Tx-Rx at same operating frequency 2.4 Ghz for wireless communication among 3 MAVs and GCS caused interference of signals leading to blocking of neighbor RC Tx.</td>
<td>3 Xbee’s for MAVs and 1 for GCS were addressed uniquely and all enabled with API data packet scheme and API module is included in the overall code of APM 2.6</td>
</tr>
<tr>
<td>Initially algorithm was tested with larger separation among Leader and Follower, but as soon the separation was narrowed, oscillations starting and Follower used to exceed the Leader and start loitering at that waypoint.</td>
<td>This issue was resolved by making the velocity control loop in the lpsi/SDC formation controller more bounded by applying tanh function.</td>
</tr>
<tr>
<td>Flying three fully autonomous aircrafts together in formation in unpredictable weather conditions (wind gusts, thermals, etc) affects the stability of formation</td>
<td>The autopilot control takes care of the wind disturbances and stabilizes the flight of the individual MAV</td>
</tr>
<tr>
<td></td>
<td>The formation flight was tested on three MICAVs in winds upto 5 m/s and velocity control so designed was responsible to maintain the formation</td>
</tr>
</tbody>
</table>
- It is designed and fabricated by NAL
- It is 450 mm wingspan pusher configuration UAV

<table>
<thead>
<tr>
<th>Component</th>
<th>Model Name</th>
<th>Manufacturer</th>
<th>Data Rate</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed sensor</td>
<td>MPXV7002DP</td>
<td>Freescale</td>
<td>50 Hz</td>
<td>Typical Pressure Accuracy = +/−2.5 Pa</td>
</tr>
<tr>
<td>RF Telemetry module</td>
<td>XBeePro 2.4</td>
<td>DigiMesh</td>
<td>250 Kbps</td>
<td>Typical Range=1.6 km, 2.4 Ghz</td>
</tr>
<tr>
<td>Onboard autopilot</td>
<td>APM 2.6</td>
<td>ArduMegaPilot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS module</td>
<td>Ublox LEA-6H</td>
<td>3DR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HILS using Pushpak airframe and servo actuators
Formation Controller (Guidance Loop): designed in MATLAB/Simulink

$X^L = \text{Leader's system states}$

$X^{F1} = \text{Follower's system states}$

$\chi_c^L = \text{Leader's heading angle}$

$\chi_c^{F1} = \text{Follower's heading angle}$

$v_c^L = \text{Leader's linear velocity}$

$v_c^{F1} = \text{Follower's linear velocity}$

$\omega_c = \text{Leader's angular velocity}$

$\omega_F = \text{Follower's angular velocity}$

$(l_{12}^a, \psi_{12}^a) = \text{actual separation and deviation angle between LF}$

$(l_{12}, \psi_{12}) = \text{estimated separation and deviation angle between LF}$

$(l_{12}^d, \psi_{12}^d) = \text{desired separation and deviation angle between LF}$
Separation-Deviation Angle Controller (SDC)

**Separation-Deviation Angle Derivative**

\[
\dot{l}_{12} = v_L \cos(\chi_L - \psi_{LF1}) - v_F \cos(\chi_F - \psi_{LF1})
\]

\[
\dot{\psi}_{LF1} = \frac{v_L \sin \psi_{LF1} - v_F \sin \lambda_1 - l_{12} \omega_L}{l_{12}}
\]

**Error Dynamics**

\[
\dot{l}_{12} = k_1 (l^d_{12} - l_{12})
\]

\[
\dot{\psi}_{LF1} = k_2 (\psi^d_{LF1} - \psi_{LF1})
\]

**LPSI Controller**

\[
v_F = \frac{k_1 (l^d_{12} - l_{12}) + v_L \cos \psi_{LF1}}{\cos \lambda_1}
\]

\[
\omega_F = \frac{\cos \lambda_1 \left( k_2 l_{12} \left( \psi^d_{LF1} - \psi_{LF1} \right) - v_L \sin \psi_{LF1} \right)}{\delta E}
\]

**Modified LPSI Controller**

\[
v_F = \frac{v_L \left( \lambda_1 - \chi_l \right) - \alpha (d_{des\_LF1\_vir} - d')}{\cos \left( \lambda_1 - \chi_l \right)}
\]
Formation control interfaced with 6dof aero model and autopilot control

**Follower MAV block**

- **Follower 6 dof model**
  - da,de, dt

**States**

\[ [V, \alpha, \beta, \phi, \theta, \psi, p, q, r, \text{lat}, \text{lon}, h] \]

**V=V_f**

Airspeed

**Energy error**

**Autopilot control block**

- Throttle command
- Bank angle

**Navroll block**

**Formation control**

**Leader 6 dof model + autopilot control loop**

**Error**

\[ (l_{12}^d, \psi_{12}^d) - \int l_{i12}, \psi_{12} \]
SILS of overall formation controller

6 dof aerodynamic model + autopilot control

Leader MAV

Follower1 MAV

6 dof aerodynamic model + autopilot control

Follower2 MAV

Relative separation and bearing angle calculation

Lpsi controller for L & F1

Lpsi controller for L & F2
6 dof aerodynamic model with autopilot control
PILS Facility setup at NAL

- Follower MAV
- Leader MAV
- QGCS
- Mission Planner
- Radio Control Transmitter
- Radio Control Receiver
- Autopilot Board APM 2.6
XBee Configuration for Multi-MAV communication

### API Scheme data format

- **7E 00 0E 00 00 00 13 A2 00 40 93 DA B8 00 56 89 23 E3**

### GCS Multiple MAV ID

<table>
<thead>
<tr>
<th>Leader Node</th>
<th>Follower1 Node</th>
<th>Follower2 Node</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SYS ID</strong></td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

### PAN ID, 16 Bit Address, Baud Rate, API Enable

<table>
<thead>
<tr>
<th></th>
<th>GCS Node</th>
<th>Leader Node</th>
<th>Follower1 Node</th>
<th>Follower2 Node</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PAN ID</strong></td>
<td>3332</td>
<td>3332</td>
<td>3332</td>
<td>3332</td>
</tr>
<tr>
<td><strong>16 Bit Address</strong></td>
<td>1001</td>
<td>3333</td>
<td>4444</td>
<td>5555</td>
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<tr>
<td><strong>Baud Rate</strong></td>
<td>57600</td>
<td>57600</td>
<td>57600</td>
<td>57600</td>
</tr>
<tr>
<td><strong>API Enable</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Flow of control in Multi-MAV setup

Leader

Host PC

FG/X-Plane

APM Mission Planer

UDP

FTDI

Compile /Upload

APM Board

XBee - 3333

Sensor Signals

Follower 1

Host PC

XBee - 4444

APM Board

Upload

APM Mission Planer

FG/X-Plane

Debug (optional)

Docklight

XBee - 6666

Host PC

XBee - 6666
Implementation in PILS

Algorithm design and development in Matlab/Simulink → Auto code generation → Port onto APM 2.6 using Arduino IDE → MP and FG linked using MAVLink protocol to APM 2.6 → MP and FG linked using UDP port

Leader and Follower mission observed on Ground Control Station

Leader GCS starts auto mission → RC Tx switched to auto

Start following Leader → RC Tx switched to guided → Follower GCS starts auto mission → RC Tx switched to auto
Flight mission of two MAVs in PILS
Formation flight test procedure

3 MICAVs fully populated → Leader-follower configuration(s) → Manual takeoff (L,F1, F2) – Stabilize and switch leader to auto and followers to guided mode → Leader performs auto mission and followers start converging and do formation → Manual land L and guided landing F1, F2 → All tracks are observed on QGCS → Follower 1 on left side and follower 2 on right side
Leader-Follower Flight Test

Leader-Follower MAVs flown in formation by NAL Team at Hoskote Lakebed, Bengaluru
- Desired Separation between Leader and Follower = 20m
- Error in relative separation = ±20m
Great thanks to:

- Director, NAL
- Dr. Ramesh G, HOD MAV UNIT
- Dr. G.K. Singh and team, FMCD
- Dr. Kamali C and Dr. Somya Ranjan Sahoo
- Flyers Vikas and Goutham
THANKS