AWEsome: An open-source test platform for airborne wind energy systems

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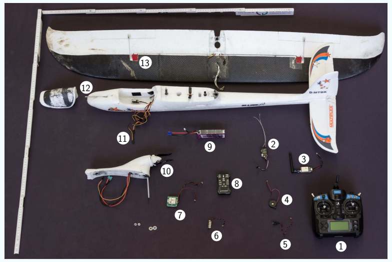
AWEsome (AWE standardized open source model environment)

- easy access to the AWE field: cross-wind flight of tethered fixed-wing aircraft
- test environment for design strategies / algorithms without high financial risk
  - cheap (< US$ 1000) → disposable
  - open source (OS)
- various tools for data logging and analysis
  - SITL simulations based on flight-dynamics model `JSBsim`
  - log files with detailed primary and processed data
  - software for data analysis
- components
  - modified off-the-shelf polystyrene model aircraft, reinforced with carbon fabric
  - flight control hardware `pixhawk` and software `ArduPlane` of `ardupilot`
  - ground control station (GCS) software `mission planner`
  - off-shore fishing rod (ground station for tethered flight)

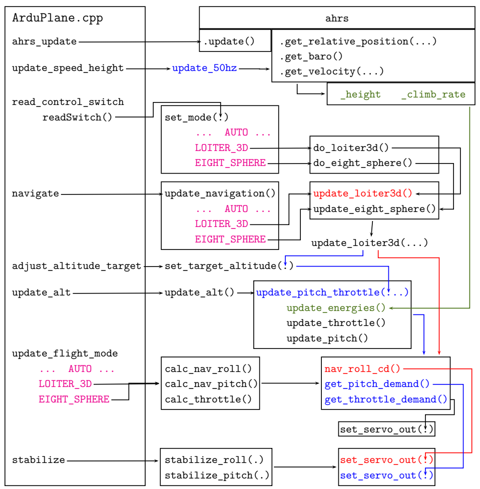


1 transmitter for remote radio control, **2 receiver** to receive signals from the transmitter, **3 telemetry** used for communication between ground control station and drone, **4 Buzzer** for audio status information, **5 safety switch** to prevent from accidental arming, **6 I2C splitter** provides three additional ports for digital peripherals, **7 GPS/compass module** provides positioning and heading data during flight, **8 pixhawk**, **9 battery** provides power, **10 propeller** provides thrust, **11 connection cables** to servos, **12 airspeed sensor** measures apparent airspeed, **13 servos** to steer the ailerons; servos for rudder and elevator are inside the fuselage

ArduPlane main control loop

`loop()` calls tasks in `ArduPlane.cpp`:

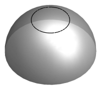
- `ahrs_update` (attitude and hight reference system)-update of the state
- `read_control_switch` selects flight mode according to position of control switch at RC transmitter
- `navigate` determines desired position and attitude and deviation
- `adjust_altitude_target` sets desired altitude
- `update_alt` determines pitch and throttle to reach desired altitude and airspeed
- `update_flight_mode` updates desired roll angle, pitch and throttle
- `stabilize` sets servos



Tethered flight modes

implemented flight modes at a tether of constant length ⇒ navigation on a hemisphere simplest periodic flight modes (piecewise constant curvature):

`LOITER_3D` (inclined) circle
⇒ tether cummulates torsion



`EIGHT_SPHERE` (inclined, rotated) figure-eight pattern
⇒ limited tether torsion

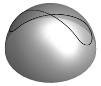
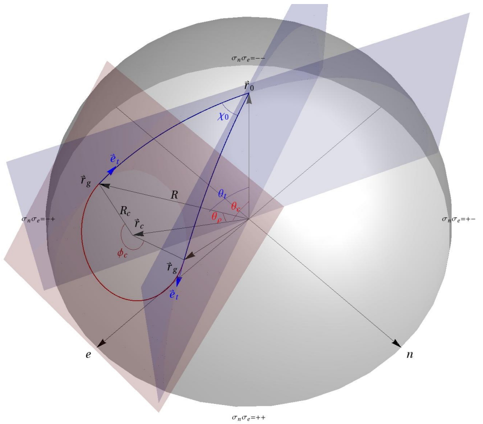


Figure-eight pattern



- consists of two great circle segments and two small (turning) circle segments
- parametrized by:
  - size: sphere radius R
  - shape: turning circle center inclination $0 < \theta_c < \frac{\pi}{2}$; turning circle opening angle $0 < \theta_\rho \le \min(\theta_c, \frac{\pi}{2} - \theta_c)$
  - attitude: elevation angle $0 \le \gamma \le \frac{\pi}{2}$; azimuth $0 \le \psi \le 2\pi$
  - orientation: $\sigma = \pm 1$
- gluing condition of great circle segments and small circle segments at transgression points $\vec{r}_{g,\sigma_n,\sigma_e}$:

$$\vec{e}_t = \vec{e}_t$$

⇒ turning circle radius

$$R_c = R \sin\theta_\rho$$

⇒ transgression point polar angle θ_t, crossing angle χ_0, turning angle ϕ_c

$$\cos\theta_t = \frac{\cos\theta_c}{\cos\theta_\rho}\,, \qquad \cos\frac{\chi_0}{2} = \frac{\sqrt{\sin^2\theta_c - \sin^2\theta_\rho}}{\sin\theta_c}\,, \qquad \sin\frac{\phi_c}{2} = \frac{\cos\frac{\chi_0}{2}}{\cos\theta_\rho}\,.$$

⇒ vectors: crossing point $\vec{r}_0$, turning circle centers $\vec{r}_{c,\sigma_e}$, transgression points $\vec{r}_{g,\sigma_n,\sigma_e}$

$$\vec{r}_0 = R\begin{pmatrix}0\\0\\-1\end{pmatrix}, \qquad \vec{r}_{c,\sigma_e} = R\cos\theta_\rho\begin{pmatrix}0\\\sigma_e\sin\theta_c\\-\cos\theta_c\end{pmatrix}, \qquad \vec{r}_{g,\sigma_n,\sigma_e} = R\begin{pmatrix}\sigma_n\sin\theta_t\sin\frac{\chi_0}{2}\\\sigma_e\sin\theta_t\cos\frac{\chi_0}{2}\\-\cos\theta_t\end{pmatrix}.$$

- all vectors are rotated by multiplying with rotation matrix

$$R(\gamma,\psi) = (\vec{e}_\gamma, \vec{e}_\psi, \vec{e}_r)\,, \qquad \vec{e}_\gamma = \partial_\gamma\vec{e}_r\,, \qquad \vec{e}_\psi = \frac{\partial_\psi\vec{e}_r}{\cos\gamma}\,, \qquad \vec{e}_r = \begin{pmatrix}\cos\gamma\cos\psi\\\cos\gamma\sin\psi\\-\sin\gamma\end{pmatrix}.$$

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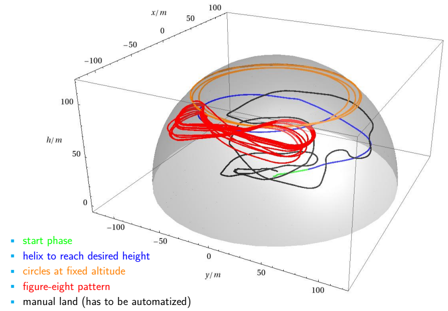
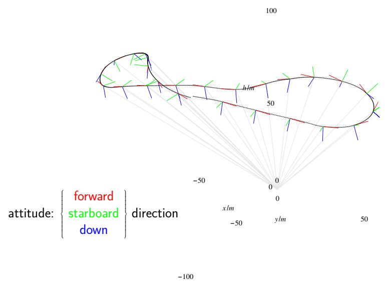
Figure-eight pattern on S^2 of radius $R = 120\mathrm{m}$ at $\gamma = 45°$

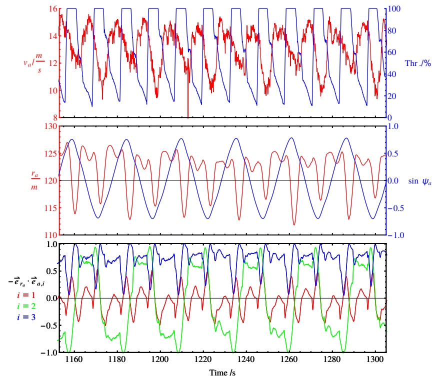


Attitude visualization



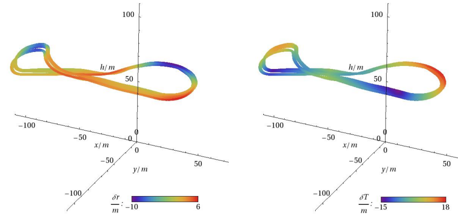
Temporal analysis

airspeed v_a, throttle,
distance r_a from center,
projection $\sin\psi_a$ of lateral position onto east,
projections of attitude (forward, starboard, down unit vectors) onto direction of $\vec{r}_a$



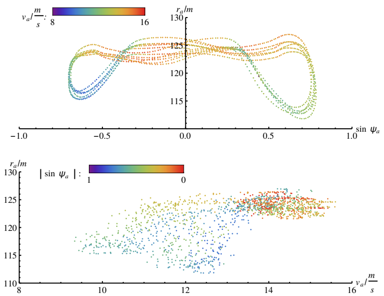
- wind speed of only $v_w = 0.42\frac{m}{s}$ ⇒ throttle especially in upwards turning circles
- periodic tether force variations visible ($r_a \propto$ tether force)
- correlations of tether force with r_a, v_a

Radial and tansversal deviation from desired path



- radial deviation maximally positive on geodesic segments where altitude is decreased → maximal tether tension
- radial deviation maximally negative on turning circles where altitude is increased → minimal tether tension
- transversal deviation positive/negative outwards/inwards of the desired path
- transversal deviation becomes zero approximately at crossing point
- transversal deviation maximally positive/negative in turning circles / on geodesics

Radius



- radius is maximal where airspeed is maximal (on geodesic segments)
- radius and airspeed are maximal in the vicinity of the crossing point

Conclusions and outlook

- successfully set up a low-cost AWE test platform
  - modified / reinforced an off-the-shelf model aircraft
  - implemented new flight modes in `ardupilot`
- demonstrated that an elementary, economic setup is sufficient for tethered flight

⇒ provided AWEsome: a suitable intuitively understandable starting point for developing / testing AWE design strategies
  - complete logging of all sensor and (processed) flight data
- planned further modifications / improvements
  - measurement of the tether force
  - implementation of a tether model in the control algorithms
  - implementation of different flight patterns
  - construction of an automatized ground station for tether reel-out and reel-in
  - implementation of the used aircraft as a SITL model
  - use of tangential and normal frame of the sphere as reference frame for navigation

Contributions very welcome!

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