UNICO I+D Project
6G-INTEGRATION-4

# E17-6G-INTEGRATION-4

# Control algorithms software model


## Abstract

This deliverable presents the conceptual and technical foundation of the control software architecture developed for the 6G-INTEGRATION-4 project, under the UNICO I+D programme. It outlines the main control strategies and energy management approaches for High-Altitude Platform Stations (HAPS) operating in long-endurance missions with hybrid hydrogen/solar power systems. The report includes detailed analysis of mission requirements, lift/drag and velocity profiles, power scenarios, and the integration of energy storage systems. The proposed framework aims to ensure optimal performance in terms of thrust-to-weight and energy efficiency for sustained autonomous operations.



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# Disclaimer

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# List of equations



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# List of Acronyms

APU – Auxiliary Power Unit

AC – Alternating Current

ANN – Artificial Neural Network

DC – Direct Current

EMS – Energy Management System

ESS – Energy Storage Systems

FLC – Fuzzy Logic Control

HESS – Hybrid Energy Storage Systems

MEA – More Electrical Aircraft

PEM – Proton Exchange Membrane

PEMFC – Proton Exchange Membrane Fuel Cell

RAT – Ram Air Turbine

RES – Renewable Energy Sources

SOC – State of Charge

MF – Membership Functions

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# Resumen Ejecutivo

Este documento contiene la definición de la arquitectura principal de HAPS frente a las especificaciones de la misión. Se han realizado diversos análisis considerando el espectro de cargas, así como estudios de flotabilidad de arrastre/velocidad. Se han definido las principales tecnologías para la realización del concepto y funcionamiento de las HAPS. Por último, se han definido las principales tecnologías a utilizar en la combinación hidrógeno/solar para el ciclo energético con almacenamiento de energía química para lograr la mejor relación empuje/energía/peso.

Los principales resultados descritos en este entregable son:

- características técnicas del 6G-INTEGRATION-4;
- escenarios operativos y perfiles de potencia;
- desarrollo de sistema de control eficiente
- investigación de un sistema de gestión de control y energía mediante algoritmos
- análisis del impacto socioeconómico; y
- análisis del potencial para la realización de nuevas acciones de I+D.

El resto del documento está redactado en inglés, de cara a maximizar el impacto del trabajo realizado en este proyecto.

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# Executive Summary

This document contains the definition of the main HAPS architecture against the mission specifications. Various analyses have been carried out considering the load spectrum, as well as drag/speed buoyancy studies. The main technologies for the realisation of the concept and operation of HAPS have been defined. Finally, the main technologies to be used in the hydrogen/solar combination for the energy cycle with chemical energy storage have been defined to achieve the best thrust/energy/weight ratio.

The main results described in this deliverable are:

- technical characteristics of the 6G-INTEGRATION-4;
- operating scenarios and power profiles.
- development of efficient control system
- Investigation of a control and energy management system using algorithms
- socio-economic impact analysis; and
- analysis of the potential for carrying out new R&D actions.

The rest of the document is written in English, to maximise the impact of the work carried out in this project.

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# 1 Introduction

The main objective of the 6G-INTEGRATION-4 (6G-INT-3) project is to demonstrate to TRL4, the technological concept of developing a hybrid autonomous aircraft based on the concept of a lighter-than-air aircraft using hydrogen as a buoyancy system and as powertrain fuel by combining instantaneous solar production with fuel cell power generation, battery and ultracapacitor support, and intelligent energy and hydrogen management.

In this deliverable, the technical characteristics of the airship have been addressed, and the different power, consumption and navigation scenarios have been investigated. Additionally, control, navigation and energy management systems have been investigated. Finally, a socioeconomic study and its environmental impact have been carried out. As well as potential future research and development actions.

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# 2 Control algorithms overview implemented

In this section the theoretical control equations will be presented, which will then be implemented in the system controller in a practical way.

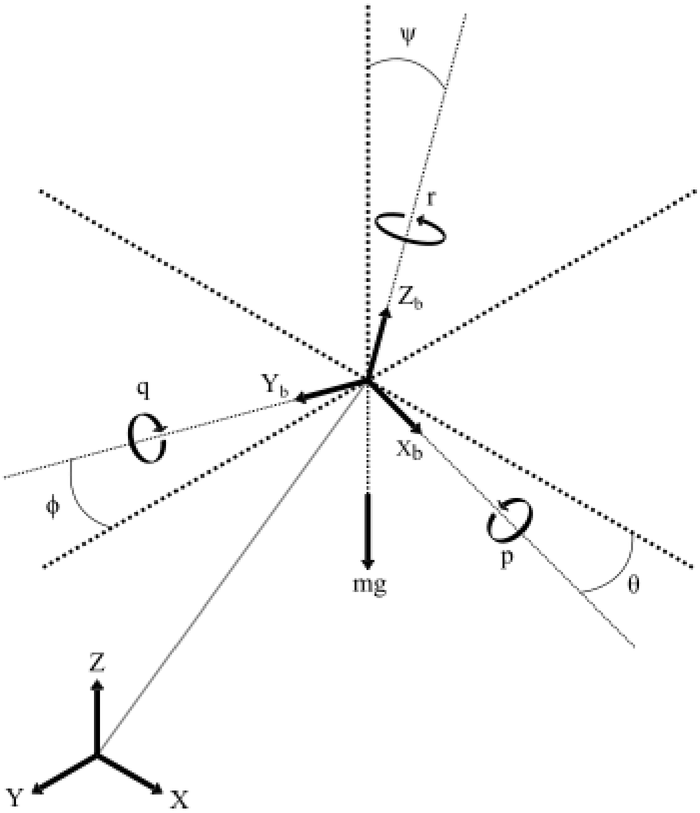


*Figure 2.1 - Axis systems used. The inertial reference frame is shown together with the moving reference frame.*

The measurements of the system will be measured according to the inertial reference system formed by the global axes; therefore, it is necessary to consider the transformation from the fixed axes to the mobile axes associated to the body of the system. To perform this transformation, use will be made of the Euler angles, which describe the orientation of a system according to the value of these angles.

The three angles will be $\phi$, which indicates the angle formed on the Y-axis, $\theta$, which indicates the angle formed on the X-axis and $\psi$, which indicates the angle formed on the Z-axis. Typically, these angles $\phi, \theta, \psi$, are the roll, pitch and yaw angles.

To perform the transformation of the axes, the rotation matrices for each of the angles will be used, combining them all in a transformation matrix from fixed axes to moving axes.

Rotation matrix for roll angle:

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$$R_{\phi}^{y} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

*Equation 2.1-Roll rotation matrix*

Rotation matrix for pitch angle:

$$R_{\theta}^{x} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\phi \end{bmatrix}$$

*Equation 2.2-Pitch rotation matrix*

Rotation matrix for yaw angle:

$$R_{\psi}^{z} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

*Equation 2.3-Yaw rotation matrix*

Combining the three transformation matrices, we obtain the transformation matrix to go from the body axis system to the global axis system:

$$R_{uvw}^{xyz} = R_{\psi}^{z} * R_{\theta}^{x} * R_{\phi}^{y}$$

$$R_{uvw}^{xyz} = \begin{bmatrix} C_{\psi}C_{\theta} & C_{\psi}S_{\phi}S_{\theta} - C_{\phi}S_{\psi} & S_{\phi}S_{\psi} + C_{\phi}C_{\psi}S_{\theta} \\ C_{\theta}S_{\psi} & C_{\phi}C_{\psi} + S_{\phi}S_{\psi}S_{\theta} & C_{\phi}S_{\psi}S_{\theta} - C_{\psi}S_{\phi} \\ -S_{\theta} & C_{\theta}S_{\phi} & C_{\phi}C_{\theta} \end{bmatrix}$$

$$R_{xyz}^{uvw} = R_{uvw}^{xyz\,T}$$

*Equation 2.4-System rotational matrix*

## 2.1 Position Control

The position control is divided into two sub-controllers, the vertical position control, in charge of controlling the total thrust of the system, and the horizontal position control (movement in the X-Y plane).Each of them consists of a proportional control for the position, followed in series by a PID control for the velocity, that is, the position control is performed by a P controller with the position error, and the control signal is used as a reference for the velocity control, using a PID for this purpose.

The position error is taken by calculating the difference between the position reference set and the measurement obtained. (The equations of the horizontal position control will be shown first).

$$e_x = X_{ref} - X$$

*Equation 2.5-X position error*



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$$e_y = Y_{ref} - Y$$

*Equation 2.6-Y position error*

This error corresponds to the difference in global coordinates of the system, however, for the correct operation of the controller, the P control must be performed with the error in local coordinates of the system, therefore, we proceed to perform the necessary transformation for it.

$$\begin{bmatrix} e_{x_{local}} \\ e_{y_{local}} \end{bmatrix} = R_b^i \begin{bmatrix} e_x \\ e_y \end{bmatrix}$$

*Equation 2.7-Transformation from global position error to local position error*

These errors will correspond to local errors, which will be used directly by the P-controller.

$$v_{x_{ref}} = P_x * e_{x_{local}}$$

*Equation 2.8-Local X velocity reference*

$$v_{y_{ref}} = P_y * e_{y_{local}}$$

*Equation 2.9-Local Y velocity reference*

Where $P_x$ and $P_y$ correspond to the proportional constants of the position controller.

The purpose of the position controller is to obtain the references to be used for linear velocity control. This controller uses the local velocity measurements to calculate the velocity error used in the linear velocity controller.

$$e_{v_x} = v_{x_{ref}} - v_{x_{local}}$$

*Equation 2.10-Local X velocity error*

$$e_{v_y} = v_{y_{ref}} - v_{y_{local}}$$

*Equation 2.11-Local X velocity error*

These errors are used in linear speed control for X and Y speed, whose output signal corresponds to the pitch and roll angle references.

$$\phi_{ref} = \left[P_{v_x} + I_{v_x} T_s \frac{1}{z-1} + \frac{D_{v_x}}{T_s} \frac{z-1}{z}\right] * e_{v_x}$$

*Equation 2.12-Pitch reference*

$$\theta_{ref} = \left[P_{v_x} + I_{v_y} T_s \frac{1}{z-1} + \frac{D_{v_y}}{T_s} \frac{z-1}{z}\right] * e_{v_y}$$

*Equation 2.13-Roll reference*

Following this structure, the vertical position control, or height control, is performed.



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$$e_z = Z_{ref} - Z$$

*Equation 2.14-Z position error*

The next step is to use this error as input to the vertical position proportional controller, the result of which will be the vertical linear velocity reference. In this case it is possible to work with the position error in the fixed inertial reference system as well as with the linear velocity.

$$v_{zref} = P_z * e_z$$

*Equation 2.15-Local Z velocity reference*

$$e_{v_z} = v_{zref} - v_z$$

*Equation 2.16-Local Z velocity error*

Finally, obtained the velocity error, it is used as input to the PID controller. The result of the control will be the total thrust exerted by the platform which carries a gravity compensation term, so that when the velocity error is zero, the system maintains a thrust equal to the gravity force suffered and therefore remains in a static flight state.

$$F_t = mR_b^i g + \frac{1}{2}\rho V^2 SC_L + \rho_f g v_f + \left[P_{v_z} + I_{v_z} T_s \frac{1}{z-1} + \frac{D_{v_z}}{T_s}\frac{z-1}{z}\right] * e_{v_z}$$

*Equation 2.17-Vertical force calculation, based on gravity effect, lift, buoyancy and control actuation*

Where:

- $mR_b^i g$ is the gravity force
- $\frac{1}{2}\rho V^2 SC_L$ is the lift force
- $\rho_f g v_f$ is the buoyancy force
- $\left[P_{v_z} + I_{v_z} T_s \frac{1}{z-1} + \frac{D_{v_z}}{T_s}\frac{z-1}{z}\right] * e_{v_z}$ is the PID actuation for height control

## 2.2 Attitude Control

The orientation control is the secondary loop of the nested control, it will receive the angular position references, as well as the orientation and angular velocity measurements of the system and will generate the moments to be applied on the platform.

The control will be carried out following the same structure as for the previous case, a proportional control will be used for the angular position control, generating the angular velocity references and in series a PID control for the angular velocity control of the system.

The error of the Euler angles of the system is obtained first.

$$e_\phi = \phi_{ref} - \phi$$

$$e_\theta = \theta_{ref} - \theta$$



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$$e_{\psi} = \psi_{ref} - \psi$$

*Equation 2.18-Pitch, Roll and Yaw error*

With the angular position error, the angular velocity references of each of the components are obtained.

$$\dot{\phi}_{ref} = P_{\phi} * e_{\phi}$$

$$\dot{\theta}_{ref} = P_{\theta} * e_{\theta}$$

$$\dot{\psi}_{ref} = P_{\psi} * e_{\psi}$$

*Equation 2.19-Pitch, Roll and Yaw angular velocity reference*

The error of angular velocities is obtained.

$$e_{\dot{\phi}} = \dot{\phi}_{ref} - \dot{\phi}$$

$$e_{\dot{\theta}} = \dot{\theta}_{ref} - \dot{\theta}$$

$$e_{\dot{\psi}} = \dot{\psi}_{ref} - \dot{\psi}$$

*Equation 2.20-Pitch, Roll and Yaw angular velocity error*

Finally, the error of the angular velocity is used to apply it on the PID control, in order to obtain the moments to be applied on the system. The moment on the X-axis is obtained through the roll component, the moment on the Y-axis is obtained with the pitch, and the moment on the Z-axis is obtained with the yaw.

$$M_x = \left[P_{\dot{\theta}} + I_{\dot{\theta}} T_s \frac{1}{z-1} + \frac{D_{\dot{\theta}}}{T_s} \frac{z-1}{z}\right] * e_{\dot{\theta}}$$

$$M_y = \left[P_{\dot{\phi}} + I_{\dot{\phi}} T_s \frac{1}{z-1} + \frac{D_{\dot{\phi}}}{T_s} \frac{z-1}{z}\right] * e_{\dot{\phi}}$$

$$M_z = \left[P_{\dot{\psi}} + I_{\dot{\psi}} T_s \frac{1}{z-1} + \frac{D_{\dot{\psi}}}{T_s} \frac{z-1}{z}\right] * e_{\dot{\psi}}$$

*Equation 2.21-Moment calculation control for X, Y and Z*



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# 3 Control Algorithms to be validated on the final HAPS design

## 3.1 Navigation Algorithm

**Program 1: Navigation**

- **Type:** Generic (common to all aircraft)
- **Function:** The Navigation program is responsible for computing the vehicle's position, velocity, and altitude by fusing measurements from GNSS (GPS), barometric sensors, and terrain databases. Its primary goal is to deliver a robust, continuous estimate of the aircraft's state.

## 3.2 Control Algorithm

### 3.2.1 Guidance Track Algorithm

**Program 2: Guidance Track**

- **Type:** Specific (customized per flight phase)
- **Function:** The Guidance Track program generates the sequence of guidance commands sent to the autopilot controller for tasks such as following a line, climbing, maintaining altitude, or landing. For the H2APS airship, its primary role is to automatically compute the flight path from user-defined waypoints, enabling autonomous navigation between points.

  **Note 1:** The "speed" parameter in the guidance blocks is not applied here; thrust control is handled by the Thrusting program (Program 5).

  **Note 2:** Altitude is not managed by this program; the H2APS achieves ascent or descent by adjusting its empty weight (Program 3).

### 3.2.2 Guidance Hold Algorithm

**Program 3: Guidance Hold Algorithm**

- **Type:** Generic (attitude control module)
- **Function:** This program implements all altitude-tracking logic by adjusting the H2APS's empty weight to induce ascent or descent according to flight phase:
- Init (default case):
  - Weight = 20 000 lb ⇒ vehicle stays on the ground.
- **Standby & Takeoff:**
  - Weight = 20 000 lb (fixed).
- **Climbing:**

    - Weight = 100 lb ⇒ fast climb (1–1.5 m/s).
- **Cruise, Loiter, Hold:**
    - Target altitude = 1 000 m.
    - A bound block on AGL implements a two-tier weight-based control:
        - If AGL < 1 000 m:
            - AGL < 990 m ⇒ weight = 50 lb (aggressive climb).
            - 990 m ≤ AGL < 1 000 m ⇒ weight = 100 lb (gentle climb).
        - If AGL > 1 000 m:
            - AGL > 1 010 m ⇒ weight = 20 000 lb (aggressive descent).
            - 1 000 m < AGL ≤ 1 010 m ⇒ weight = 17 000 lb (gentle descent).
    - Weight changes are applied as ramps to avoid sudden altitude jumps.
- **Landing:**
    - Same logic as Cruise, but with target altitude = 300 m.
- **Flare:**
    - Weight = 20 000 lb ⇒ forces descent onto the runway.
- **Braking:**
    - Weight = 25 000 lb ⇒ ensures the airship comes to a stop during rollout.

### 3.2.3 Thrusting Algorithm

**Program 4: Thrusting**

- **Type:** Specific
- **Function:** This program manages the generation of thrust for the H2APS according to the active flight phase, and controls the brake and vector thrust angle.

**Phase Behavior:**

| Phase | Thrust (RPM) | Brake | Thrust Angle (°) |
|---|---|---|---|
| Init | 0 | Activated | 0 |
| Standby | 1 500 | Activated | 0 |
| Takeoff | Ramp-up to maximum | Deactivated | 0 |

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| | | | |
|---|---|---|---|
| **Climbing** | **Ramp-up to maximum** | **Deactivated** | **0** |
| **Cruise** | **Controlled (PID)** | **Deactivated** | **0** |
| **Loiter** | **Controlled (PID)** | **Deactivated** | **0** |
| **Flare** | **1 500** | **Activated** | **0** |
| **Landing** | **Controlled** | **Deactivated** | **0** |
| **Braking** | **Variable** | **Activated if IAS < 3 m/s** | **180** |

*Table 3.1-Phase behaviour thrust values*

**Key Components:**

**Thrust Direction (vectorThrustAngle):**

- Set to 0 in all phases except Braking (0.5) to reverse thrust for effective deceleration.
- Ramped to prevent abrupt transitions.

**Brake Control:**

- Engaged during Init and Standby.
- Disengaged at Takeoff to allow departure.
- In Braking, engages only if IAS is between 0 and 3 m/s, ensuring smooth rollout.

### 3.2.4 Yawing Algorithm

**Program 5: Yawing**

- **Type:** Specific (tailored for two lateral engines).
- **Function:** The Yawing program governs the H2APS's yaw axis by applying differential thrust between its two side-mounted engines, eliminating the need for aerodynamic surfaces. First, it computes the yaw error by comparing the Desired Heading with the current Heading. This

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error is processed by a PID controller, producing the signal Yawing u4 before saturation. For enhanced stability and accuracy, this output is further compensated using the actual body-axis Z angular velocity.

Next, the yaw command is allocated between the engines: the right engine's RPM is increased by half the yaw signal (+u4/2) and the left engine's RPM is decreased by the same amount (–u4/2). This ensures that the combined thrust maintains forward propulsion, while the thrust differential generates the required yaw moment. All RPM adjustments are ramped to prevent abrupt transitions.

### 3.2.5 Pitching Algorithm

**Program 6: Pitching**

- **Type:** Adapted (operational without control surfaces).
- **Function:** This program manages the H2APS's pitch axis in Automatic mode through the following sequence:

1. Reference Generation:
   Computes the desired pitch angle from an energy-error metric using a predefined lookup function.
2. PID Control:
   Compares actual pitch with the desired value and produces a corrective command via a PID loop.
3. Filtering and Saturation:
   Smooths and bounds the command to prevent abrupt or excessive maneuvers.
4. Command Dispatch:
   Sends the processed pitch command to the internal control system.

### 3.2.6 Rolling Algorithm

**Program 7: Rolling**

- **Type:** Adapted (without control surfaces)
- **Function:** This program controls the H2APS's roll axis in Automatic mode through the following sequence:

1. **Reference Generation:**
   Derives the desired roll angle from the planned flight path (heading and groundspeed).
2. **PID Control:**
   Compares the current roll angle with the desired value and issues a corrective command via a PID loop.
3. **Filtering and Saturation:**
   Smooths and bounds the command to prevent abrupt or excessive bank manoeuvres.
4. **Command Dispatch:**
   Sends the processed roll command to the internal control system.

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### 3.2.7 Energy Control Algorithm

**Program 8: Energy Control**

- **Type:** Generic (tailored to specific requirements)
- **Function:** The Energy Control block quantifies the vehicle's energy discrepancies by comparing desired versus actual energy states, based on Flight Path Angle (FPA) and Indicated Airspeed (IAS). Its outputs feed downstream control modules (thrust, attitude), support diagnostics, and facilitate future energy-based control extensions.

1. Rate Limiting:
   - Smooths the desired FPA command to prevent abrupt changes.
   - Limits: ±0.01 rad/s.
   - Output: *Limited FPA*.
2. **Energy Error Computation:**
   - Inputs:
     - *FPac*: rate-limited FPA.
     - *Vc*: indicated airspeed (IAS).
   - Outputs:
     - *EdistEr*: energy distribution error (kinetic vs. potential).
     - *ErateEr*: energy rate error.
     - *DesEr*: total desired energy.
     - *DesDisEr*: desired energy distribution.
3. **Signal Distribution:**
   - Generated errors are used for:
     - Thrust and attitude control.
     - Energy-state diagnostics.
     - Integration with standard architectures (e.g., future energy-based control logic).

### 3.2.8 Control to Servo Algorithm

**Program 9: Control to Servo**

- **Type:** Physical control interface.
- **Function**: This program aggregates all control signals from the various modules (Rolling, Pitching, Thrusting, Yawing, Braking, etc.) and routes them to the system actuators. In a hardware-equipped platform, it would drive servos for control surfaces, brakes, and motors. On the H2APS, these outputs are used for logical control or within simulation.



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# 4 Flight Phases

Each phase represents an operational state of the H2APS airship, associated with a specific behavior:

- **Standby**
  The airship remains stationary, with its engines held at a constant 1 500 RPM.
- **Takeoff**
  The takeoff phase: the H2APS progressively increases its engine speeds to achieve lift-off.
- **Climbing**
  In this phase, the airship gains altitude by reducing its empty-weight ballast.
- **Cruise**
  The vehicle maintains a constant altitude above ground level (AGL). A two-point altitude control logic is employed to hold the selected flight level.
- **Loiter**
  The airship fixes on its current GPS position and flies a circular pattern around that point, maintaining the predefined altitude.
- **Hold**
  Constant-speed phase: the H2APS flies straight ahead at a specified altitude, without following a predefined waypoint track.
- **Landing**
  In this phase, the airship automatically locates the runway threshold and initiates a descent toward a preset approach altitude.
- **Flare**
  Landing sub-phase: upon reaching the runway threshold, the airship executes a controlled, gradual descent until touchdown.
- **Braking**
  The engines reverse thrust to provide smooth, progressive deceleration until the H2APS comes to a complete stop.

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# 5 Flight Modes

In addition to the discrete flight phases, the vehicle control modes determine the source of command inputs:

- **Manual Mode**
  The airship is controlled directly from the pilot's cockpit via physical control interfaces.

- **Automatic Mode**
  The system follows a pre-programmed flight plan and responds to high-level commands such as:
  - Initiate Takeoff
  - Execute Landing
  - Maintain Circular Pattern (Loiter)
  - Fly Straight without a Defined Track (Hold)

**6. Veronte Ops Interface Buttons**
One of the key elements of the Veronte Ops tab is the set of buttons through which the operator can manually select the current flight phase. For the H2APS airship, a dedicated button has been defined for each phase. In addition to manual selection, automatic transitions between phases can be configured. These transitions occur autonomously when one or more user-defined conditions are met.

**Defined Transitions for H2APS**

- **Transition 1: From Takeoff Phase to Climbing Phase**
  **Conditions:**
  1. Indicated Airspeed (IAS) > 11.5 m/s
  2. Previous phase = Takeoff
  3. Engine speed > 200 RPM
  4. Airship within the defined TKO AREA
- **Transition 2: From Climbing Phase to Cruise Phase**
  **Conditions:**
  1. Above Ground Level (AGL) > 1 000 m
  2. Previous phase = Climbing
- **Transition 3: From Landing Phase to Flare Phase**
  **Conditions:**
  1. Airship within the Start of Runway area
  2. AGL between 290 m and 310 m
  3. Previous phase = Landing
- **Transition 4: From Flare Phase to Braking Phase**
  **Conditions:**

1. AGL < 2 m
2. Previous phase = Flare

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# 6 Summary and Conclusions

This deliverable includes:

- **Control systems development**
  Nine modular programs—Navigation, Guidance Track, Guidance Hold, Thrusting, Yawing, Pitching, Rolling, Energy Control, and Control-to-Servo—that enable fully autonomous flight without conventional aerodynamic surfaces.
- **Key algorithms**
  - Fusion of GNSS, barometric, and terrain data for robust state estimation
  - PID-based control of attitude and thrust
  - Ballast variation for precise altitude control
  - Energy management based on kinetic and potential energy errors
- **Flight phases**
  Standby, Takeoff, Climbing, Cruise, Loiter/Hold, Landing, Flare, and Braking.

- **Flight modes**
  Manual Mode (direct pilot control) and Automatic Mode (pre-programmed flight plan with high-level commands).

These elements together establish a comprehensive autonomous control framework for the H2APS platform.

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