Preliminary Design

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Contents

1 Introduction

This document outlines and documents the conceptual and preliminary design considerations for pigeon. The conceptual design is the early high-level process to establish over all needs and design goals. The preliminary design is used to determine features of the basic components/subsystems.

The conceptual design is the first and most important phase of the system design and development process [1]. Typically, the appropriate starting point is to identify the problem and the associated definitions of need at a conceptual level [1].

2 Conceptual Design

This section is divided into a few subsections to cover each conceptual design group independent of one another. An early attempt of establishing a foundation describing the primary aircraft components, configuration, and classification is made. By the end of this section the reader should have an understanding of what the objectives are for the aircraft, its classification, and conceptual design features. It is also a primary objective to list other "standard" aircraft of similar classification and configuration to assist in defining realistic baseline requirements.

2.1 Design Goals

This section outlines the overall baseline requirements that the aircraft shall be constrained to. Research has been done to get a general understanding of what the hobbyist's average system consists of. The chosen aircraft are of similar configuration that the pigeon will have. This research is summarized in Table 1.

Table 1: Short list of remote-controlled aircaft of similar configurations and some of their components.

Plane	Wing Span [mm]	Length [mm]	Flying Weight [g]
H-King (PNF) P-51D Moonbeam McSwine	750	648	425
Durafly Tundra V2	1300	920	1150
H-King (ARF) Savage Bobber	1000	700	650
Avios (PNF) Grand Tundra	1700	1260	—
Durafly Ugly Stick V2	1100	950	1050
H-King Crusader	1200	1000	990

The goals that the pigeon aim to achieve **shall** be to give a platform for basic avionics research to be conducted on. Starting goals consist of having a basic remote controlled aircraft that has stable flight. Once this has been achieved, the desired goal is to implement autonomous components, research, and further engineering on the aircraft. However, before this can be achieved baseline requirements must be met.

The listed remote-control aircraft can be considered "introductory" as they are budget, lightweight, and do not have a high flight weight (the maximum amount of weight the aircraft can sustain and still become airborne). An average weight of a rc-plane can be range from 1134-1588 grams (2.5-3.5 pounds). From Table 1, a lot of these aircraft come close to carrying double their own weight. Using these aircraft's materials and designs as inspiration should, theoretically at least, allow similar numbers to be met. Therefore, the pigeon **shall** have a weight of no more than 11588 grams with a flying weight of 853 grams. The flight weight is the average of those in Table 1. The maximum weight of any component will most likely be the power supply. Preliminary research of the largest battery used by the aircraft listed above is a 4500 mAh LiPo battery. These batteries have a weight of about 662 grams. That leaves about 191 grams for the other components such as the on-board computer, actuators, microcontrollers, cameras, and other sensors.

Preliminary research shows that an average speed of these entry level model planes range from 64 to 97 kph (40 to 60 mph). Considering that this is a research focused aircraft, speed is not a pressing matter; however, it does correlate to the maximum lift force which may need to be in the upper end of the distribution to be able to accommodate increasing demands for weight as new components/sensors are added. As a starting point, the desired baseline speed **shall** to be above 64 kmh.

Flight time for an average rc-plane is 15-20 minutes. Considering more power will be utilized by the added electronics for the sensors, on board computer, and microcontrollers, flight time may be impacted by this. Therefore, the flight time of the pigeon **shall** be no less than 10 minutes.

2.2 Classification

The pigeon is to be a hybrid radio-controlled/autonomous aircraft system. It has no intent of modeling after any other real life aircraft, otherwise known as being a flying model. The radio-controlled system, as any other typical remote controlled aircraft, has a transmitter with the pilot operating it from the ground. The radio-controlled portion will be designed first along with the aircraft to ensure that the system is capable of stable flight.

Once this has been achieved, the autonomous dual to the system will begin to be introduced in phases. These phases, subject to change, include take off, landing, collision avoidance, way point following, etc. These phases, however, do not account for internal engineering efforts such as software design, control design, filtering, etc. These concepts will be flushed out in more detail at a later date.

2.3 Primary Aircraft Components and Configuration

The basic components of the aircraft are: wing, fuselage, horizontal tail, vertical tail, engine, and landing gear. These components are essential in describing the plane. A high level configuration for each is to be described. The terminology convention follows [1]. The wing configuration **shall** be a mono-plane, high wing, rectangular, and fixed wing. The tail configuration **shall** be an aft tail, conventional, and fixed. The propulsion system **shall** be a single-engine placed in front of nose, tractor, and propeller driven. The landing gear configuration **shall** be a fixed tail gear. The fuselage configuration **shall** be an unpressurized cabin where the electronic components will seat. The aircraft **shall** be built of Expanded polypropylene (EPP) is an extremely resilient variety of foam, often used in basic trainers, which take considerable abuse from beginners, PLA plastic, and carbon fiber rods. The subsystem configuration **shall** have a conventional primary control surfaces, fly-by-wire power transmission, battery will be inside the fuselage, and the aircraft **shall** store cameras, sensors, and other electronics on

3 Preliminary Design

3.1 Weight Buildup

The total weight is composed of different components of the aircraft.

$$W_{TO} = W_{PL} + W_A + W_B + W_E \tag{1}$$

Which are the total weight, payload weight, battery weight, and the empty weight. This can be rearranged into the form of Equation 2.

$$W_{TO} = \frac{W_{PL} + W_A}{1 - \frac{W_B}{W_{TO}} - \frac{W_E}{W_{TO}}} \tag{2}$$

3.1.1 Payload weight

Payload weight of the UAV is the net carrying capacity of the aircraft. This includes cameras sensors, camera, radar, etc. These values are determined by the specification sheet as well as a safety factor $Sf = 1.5$.

```
Sf      = 1.5;                                      # Safety factor
w_cam   = 50;                                       # Camera weight
w_lidar = 50;                                       # Lidar weight

global W_PL;
W_PL    = Sf*(w_cam + w_lidar);                     # Payload weight

disp(W_PL);                                         # Display the payload weight
```

```
octave> octave> octave> octave> octave> octave> octave> 150
```

3.1.2 Autopilot weight

This is the weight that contributes to the flight operations of the aircraft. In the instance of the pigeon, it consists of both radio systems and autopilot. The mass of the inertial measurement unit (IMU) devices are very small relative to the other autopilot pieces. These include sensors such as altimeter, GPS, gyroscope/accelerometer.

```
w_pc  = 46;                                     # Onboard PC weight
w_mc  = 25;                                     # Microcontroller weight
w_rad = 27.22;                                  # Radio reciever weight
w_imu = 50;                                     # IMU weights

global W_A;
W_A   = Sf*(w_pc + w_mc + w_rad + w_imu)        # Autopilot weight
```

```
octave> octave> octave> octave> octave> W_A = 222.33
```

3.1.3 Battery Weight

The pigeon is a battery-driven aircraft. The battery weight is a major contributor to the weight buildup of the aircraft. [1] shows that for a propeller-driven aircraft, its battery weight ratio can be written as show in Equation 3. g is the gravity constant, η_P is the propeller efficiency, E_D energy density of the battery, R is the desired range, C_L is the cruise lift coefficient, and C_D is the drag due to the aircraft configuration.

$$W_B = 1.05\Big(\frac{g}{\eta_P E_D}\frac{R}{C_L/C_D}\Big) \tag{3}$$

The propeller efficiency has typical values ranging from 0.6 through 0.8. For the sake of adding safety factors in the design, the low END of the efficiency shall be used. These values can be seen in Figure 1. The range can be determined from Equation 4. V_C denotes the cruising velocity. Preliminary research shows that average starter RC aircraft velocities rage from 64 to 97 kph. Solving for R is simple, and we have defined the flight time to be about 10 minutes. The output of Figure 2 calculates the estimated range. The propeller efficiency is show in Figure 3 which is taken from [1]. The gravity constant is introduced in Figure 4. Figure 5 shows the calculation of the battery's estimated energy density. To calculate this value, it is assumed that the flight time from the design requirement in subsection 2.1. Using the ampere-hour rating, dividing it by the design flight time gives the estimated current from the battery. This current is used to estimate the power output of the battery so that the energy density can be estimated. The weight of the battery can then be estimated using the calculation in Figure 6. The estimate shows that the battery will be about 10% of the aircraft's total weight.

```
global C_D;
global C_L;

C_D = 0.03;                             # Zero-lift drag coefficient: fixed landing gear
C_L = 1.2;                              # Maximim lift coefficient
```

Figure 1: Common drag and lift coefficients used in preliminary design.

$$t_C = \frac{R}{V_C} \tag{4}$$

```
R = (10) * (64 * (1000/60))                          # min * m/min
```

Figure 2: Rane calculation for the pigeon.

```
R = 1.0667e+04
```

```
eta_p = 0.6;                                         # Propeller efficiency
```

Figure 3: Propeller efficiency estimate.

```
g = 9.81;                                            # m/s^2
```

Figure 4: Gravity constant.

```
i_b = 4500 / (10) / (1/60) * 0.001;                  # A
P_b = 2.2 * i_b;                                     # v
m_b = 745 * 0.001;                                   # kg
t_s = 10 / 60;                                       # s
E_D = P_b*t_s/(m_b)
```

Figure 5: Calculation of the estimate for the battery energy density.

```
octave> octave> octave> E_D = 13.289
```

```
global W_B;
W_B = 1.05*((g/(eta_p*E_D*3600)) * (R/(C_L/C_D)))
```

Figure 6: Estimate of the battery weight.

```
W_B = 0.095696
```

3.1.4 Empty Weight

The empty weight fraction in mainly the weight that includes the structure/airframe, engines, landing gear, and systems. Because the aircraft to this point has only bees designed conceptually, there is no geometry, sizing, or material. According to [1], the empty weight fraction can vary from 0.5 to 0.9. The empty weight fraction can be mathematically modeled by Equation 5,

$$\frac{W_E}{W_{TO}} = aW_{TO} + b \tag{5}$$

The coefficients, a and b, vary based on the different UV types. In the case of small RC vehicles the values are as defined in Figure 7. The equation Equation 5 and coefficients in Figure 7 are based of British units, therefore the values calculated must be converted

```
global a_em;
global b_em;

a_em = -0.0029;
b_em = 0.87;
```

Figure 7: Weight coefficients of RC aircraft.

Noting the form of Equation 5, W_{TO} is on both sides of the equation Equation 2. These result in a set of nonlinear equations. The solution of these is shown in Figure 8. The result shows that $W_{TO} = 2548.7$ grams.

```
function y = f(x)
global W_PL;
global W_A;
global W_B;
global a_em;
global b_em;

# Gram to pound
g_to_lb = 0.002204623;

# Convert all weights
w_pl = W_PL * g_to_lb;
w_a  = W_A  * g_to_lb;
w_b  = W_B  * g_to_lb;

# Equation
y = 0;
y = (w_pl + w_a)/(1 - (w_b) - (a_em*x + b_em)) - x; # lb
endfunction

[x, fval, info] = fsolve (@f, 0);
x *= 453.5924                                       # g
```

Figure 8: Solution of the total weight of the aircraft.

```
> > > > > > > > > > > > > > > > > octave> octave> octave> x = 2548.7
```

3.2 Wing and Engine Sizing

This phase of the preliminary design is used to determine the wing reference area, S_{ref}, and engine thrust, T. Unlike determining the weight buildup, which heavily relied on statistics, this phase is solely based on the specified aircraft performance requirements and flight mechanics theory. The technique used is called "Matching Plot", which was initially developed by NASA [1].

The aircraft performance requirements that are utilized to size the aircraft in this phase are defined in Table 2. The stall speed is the minimum speed at which an airplane must fly to produce lift. The maximum speed is the fastest that the aircraft can, theoretically, travel. Max rate of climb is the theoretical maximum climb rate. The ceiling in the highest altitude that the aircraft may fly and produce enough lift to sustain its weight.

The Matching Plot technique is performed in six steps

1. Derive one equation for each aircraft performance requirement (W/P or T/W as a function of W/S)
2. Sketch all derived equations in one plot
3. Identify the acceptable region inside the regions that are produced by the axes and the graphs. Determine the design point (i.e., the optimum selection)

Table 2: Performance requirement variables and description.

Variable	Meaning
V_s	stall speed
V_{max}	max speed
ROC_{max}	max rate of climb
S_{TO}	takeoff run
h_c	ceiling

4. From the design point, obtain two numbers; corresponding wing loading; $(W/S)_d$ and corresponding power loading; $(W/P)_d$
5. Calculate the wing area and engine thrust from these two values, since the aircraft maximum takeoff weight W_{TO} has been previously determined in Figure 8.

A "typical" plot for a propeller driven UAV is shown in Figure 9. The equations of interest are outlined in **??**. Each equation plots W/P as a function of W/S. The first equation plots the stall speeds, the second plots the maximum speed, the third plots the takeoff run distance, the fourth plots the rate of climb, and the final equation plots the ceiling. Let K be the induced drag factor, η_p be the propeller efficiency, C_{DG} be the UAV drag coefficient at the ground, μ be the runway friction coefficient, σ be the air density ration, and $(L/D)_{max}$ denotes the maximum lift to drag ratio [1].

$$\begin{array}{r|ll}
\text{Stall} & \left(\frac{W}{S}\right)_{V_s} & = \frac{1}{2}\rho V_s^2 C_{L_{max}} \\
\text{Maximum speed} & \left(\frac{W}{P_{SL}}\right)_{V_{max}} & = \frac{\eta_P}{\frac{1}{2}\rho_o V_{max}^3 C_{D_o}\frac{1}{\frac{W}{S}} + \frac{2K}{\rho\sigma V_{max}}\frac{W}{S}} \\
\text{Takeoff Run} & \left(\frac{W}{P}\right)_{S_{TO}} & = \frac{1-\exp(0.6\rho g C_{D_G} S_{TO}\frac{1}{W/S})}{\mu-(\mu+\frac{C_{D_G}}{C_{L_R}})[exp(0.6\rho g C_{D_G} S_{TO}\frac{1}{W/S})]^{V_{TO}}} \\
\text{Rate of Climb} & \left(\frac{W}{P}\right)_{ROC} & = \frac{1}{\frac{ROC}{\eta_p}+\sqrt{\frac{2}{\rho\sqrt{\frac{3C_{D_o}}{K}}}\frac{W}{S}}\left(\frac{1.155}{(L/D)_{max}\eta_p}\right)} \\
\text{Ceiling} & \left(\frac{W}{P_{SL}}\right)_{C} & = \frac{\sigma_C}{\frac{ROC_C}{\eta_p}+\sqrt{\frac{2}{\rho_c\sqrt{\frac{3C_{D_o}}{K}}}\frac{W}{S}}\left(\frac{1.155}{(L/D)_{max}\eta_p}\right)}
\end{array} \tag{6}$$

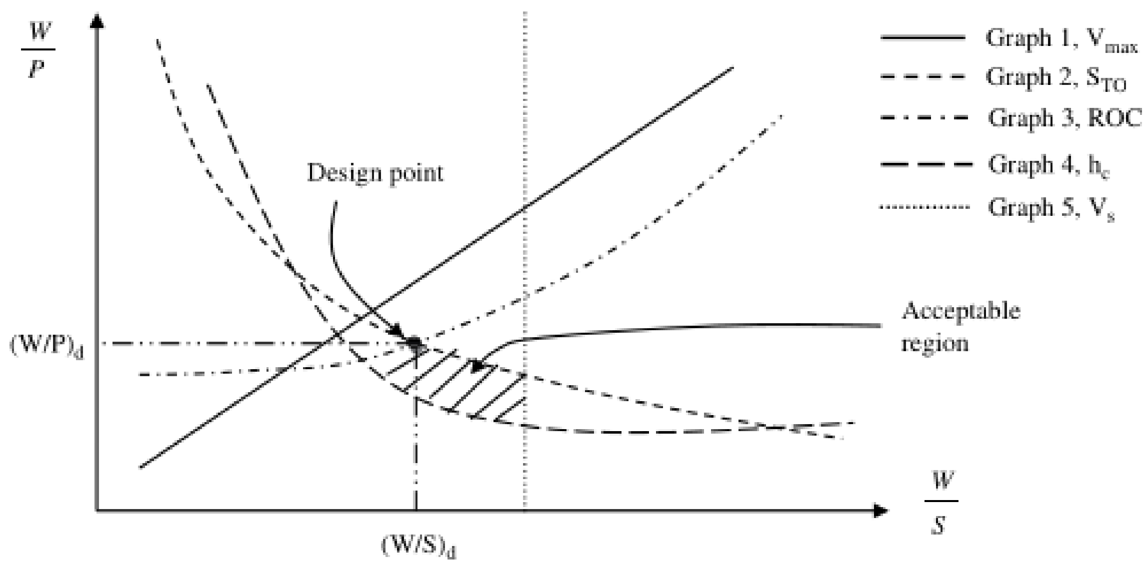

Figure 9: Matching plot for a prop-driven fixed-wing UAV

References

[1] Mohammad H. Sadraey. *Aircraft Design.* Wiley, September 2012.