Predicting birds' flight range

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Introduction

Flight is a computer program that accompanies Pennycuick [2008] which in detail discusses the theory behind bird flight. However, there are two drawbacks with the program. First, it is only available for Windows OS, and second, it requires manual imputation of bird measurements which is a tedious process when one has thousands of birds to analyse. Thus, the aim of this project is to implement in R, range estimation methods. R runs on all major operating system and the package is able to read files from a path, with multiple bird samples.

The theory behind flight mechanism has evolved over time. Pennycuick [1975] used Breguet equations intended for range estimation in fixed wing aircraft. Later ornithologists had hypotheses that in long-distance bird migration a more complex process occurs. And these were confirmed by field study where samples of birds were weighed before migration and after migration. Wind tunnel studies were also done to determine the aerodynamics of birds, that is, the body components that contribute to lift and drag. Considering the tremendous distances covered by migrating birds, at great cost, this branch of ornithology is more concerned with the mechanical and chemical process involved during migration.

Migration

Bird migration is influenced by seasonal patterns, primarily for food and breeding. Studying bird migration takes more into account than general flight. The distance covered during migration varies widely between species, and therefore it is of interest to understand physiological components that explain differences in range. Estimation of flight range in migrating birds aids in estimating flight time therefore number of stops for feeding and resting before final destination (hot-spots). In ornithology, flight range is important because it gives insight into fuel consumption, energy requirements, feeding habits, resting time duration. While this can be achieved by geo-tagging birds before migration, it is neither possible for all species (example in the case of extinct species or rare bird species) nor economical. In addition, a good number will be victims of predation, diseases, weather and collisions. What are the consequences if birds have to migrate longer distances due to interference with hot-spots, either due to human activity or climate change.

Methods

Mechanics of Flight

Mechanics of flight in birds requires more than a set of wings. For example penguins have wings but yet they do not fly. Pennycuick [2008] using Flight program shows that for a penguin to fly it requires a wing beat frequency equivalent to a hummingbird's. The wing beat frequency is proportional to the all-up body mass, wing span, wing area, acceleration due to gravity and air density. Therefore, in the penguin example, this implies comparing these physical characteristics between penguins and hummingbirds (gravity and air density as constants).

Pennycuick [1975] determined that five bird body measurements are necessary in estimating the flight range of birds. These are:

- **All up mass**: The body mass (Kg.) including contents of the crop, fuel (fat mass), and any other equipment the bird has to carry for the duration of the flight.
- **Wing span**: In meters measured from tip to tip of the fully outstretched wings.
- **Fat mass**: Mass of fat that is consumable as fuel.
- **Order**: The taxon the bird belongs to (asserine vs non-passerine). These two taxons in theory have different metabolism rates.
- **Wing area**: Area of both wings projected on a flat surface, including the body part in-between the wings.

Outline method 1 based on Brequet equations.

This method is intended for passerines with body mass less than 50 grams. Below is a list of constants (variable definition within the package).

- Profile power constant (ppc = 8.4). This can also be adjusted.
- Energy content of fuel per kg e (eFat = 4 * 10 ˆ 7)
- Acceleration due to gravity g (g = 9.81)
- Mechanical conversion efficiency η (mce= 0.23).
- Induced power factor k (ipf= 1.20)
- Ventilation and circulation power R (R = 1.10)
- Air density at flight height ρ. This can be changed according to altitude the bird species is known to fly (default airDensity = 1.00).
- Body drag coefficient $C_D b$(bdc = 0.10)
- Basal metabolic rate Π_m empirical constants
  - alpha passerines = 6.25, alpha non-passerines = 3.79
  - delta passerines = 0.724, delta non-passerines = 0.723
- Step1: With all-up mass and fat mass defined, the first step is to derive the fuel ratio.

$$fuel\ ratio = \frac{fat\ mass}{all - up\ mass}$$

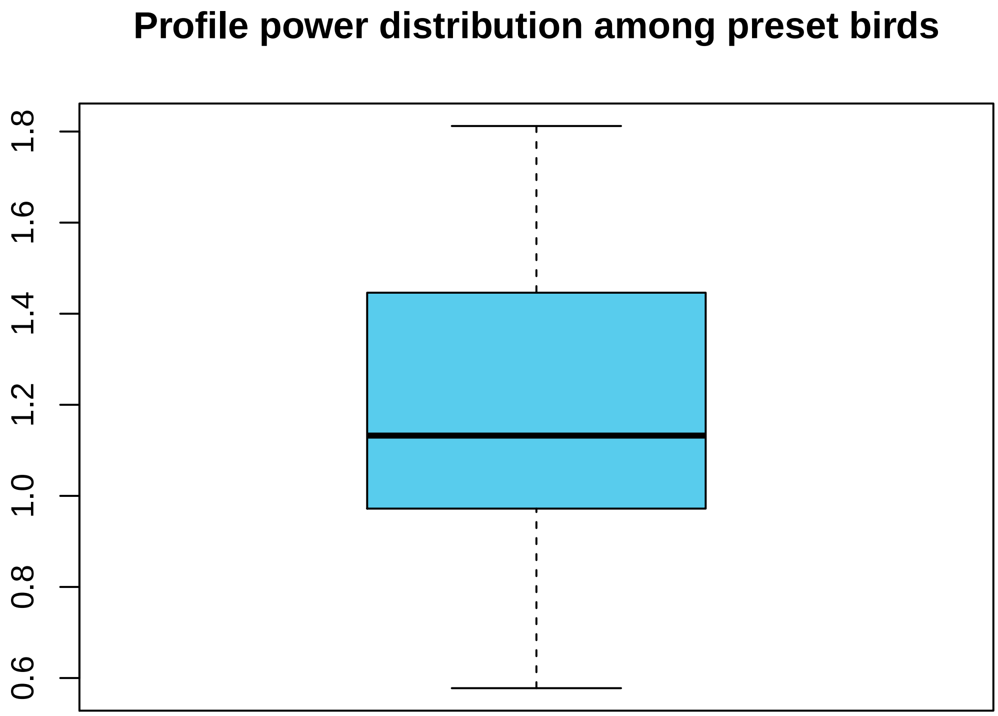
Next calculate *profile power ratio* alternative to defining it as 1.20 for each bird as was the case in the initially for these models. Instead the profile power constant is used to derive the profile power ratio. In this case the equation below provides a better individual estimate.

$$X_1 = \frac{C_{pro}}{R_a}$$

Where the $profile\ power\ constant = 8.4$

$$R_a = \frac{B^2}{wing\ area}$$

The box-plot below shows the distribution of profile power ratio of the preset birds.



In Pennycuik's earlier version, a table is provided for interpolation of metabolic power ratio based on body mass (at start of flight) and the wing span. However, in this implementation, the metabolic power ratio is calculated using the formulas provided in the book. Theory states that metabolic power is required through out irrespective of what the bird is doing.

$$X2 = \frac{6.03\ \alpha\ \eta\ \rho^{0.5}\ B^{3/2} M^{\delta-5/3}}{k^{3/4} g^{5/3}}$$

Where α and δ are constants from basal metabolism (see equation below), ρ as air density, B as wing span, and M as body mass.

- Basal metabolism for passerines:

$$\Pi_m = \alpha M^{\delta} \alpha = 6.25 \delta = 0.724$$

- Basal metabolism for non-passerines:

$$\Pi_m = \alpha M^{\delta} \alpha = 3.79 \delta = 0.723$$

With both metabolism power ratio and profile power ration defined, enables interpolation of the drag (D) from the table below.

Factor Table

x1Plusx2

B

C

D

0.00

1.360

1.140

1.000

0.25

1.386

1.458

0.824

0.50

1.452

1.783

0.706

0.75

1.515

2.115

0.621

1.00

1.574

2.453

0.556

1.25

1.631

2.795

0.506

1.50

1.684

3.141

0.465

1.75

1.735

3.490

0.431

2.00

1.784

3.841

0.402

2.25

1.830

4.195

0.378

2.50

1.875

4.550

0.357

2.75

1.918

4.907

0.339

3.00

1.959

5.266

0.322

3.25

1.999

5.625

0.308

3.50

2.038

5.986

0.295

3.75

2.075

6.348

0.283

4.00

2.111

6.711

0.273

4.25

2.146

7.074

0.263

4.50

2.180

7.438

0.254

4.75

2.213

7.803

0.246

5.00

2.246

8.168

0.238

```r
gen.table2()
```

```
##    x1Plusx2     B     C     D
## 1      0.00 1.360 1.140 1.000
## 2      0.25 1.386 1.458 0.824
## 3      0.50 1.452 1.783 0.706
## 4      0.75 1.515 2.115 0.621
## 5      1.00 1.574 2.453 0.556
## 6      1.25 1.631 2.795 0.506
## 7      1.50 1.684 3.141 0.465
## 8      1.75 1.735 3.490 0.431
## 9      2.00 1.784 3.841 0.402
## 10     2.25 1.830 4.195 0.378
## 11     2.50 1.875 4.550 0.357
## 12     2.75 1.918 4.907 0.339
## 13     3.00 1.959 5.266 0.322
## 14     3.25 1.999 5.625 0.308
## 15     3.50 2.038 5.986 0.295
## 16     3.75 2.075 6.348 0.283
## 17     4.00 2.111 6.711 0.273
## 18     4.25 2.146 7.074 0.263
## 19     4.50 2.180 7.438 0.254
## 20     4.75 2.213 7.803 0.246
## 21     5.00 2.246 8.168 0.238
```

In calculating the lift:drag ratio, the disk and equivalent flat-plate areas of a bird are important. The disc area (S_d) is the area of complete circle under which the wing span is the diameter, while the equivalent flat-plate area is a product of the frontal area and drag coefficient of a bird.

$$S_d = \frac{\pi B^2}{4}$$

$$A = S_b C_{Db} S_b = 0.00813 m^{0.666} C_{Db} = 0.1$$

Note that there is a difference here between the two books. In the earlier version the equivalent flat-plate area is defined as:

$$A = (2.85 \times 10^{-3}) M^{2/3}$$

Next step calculate effective lift:drag ratio from the formula:

$$\left(\frac{L}{D}\right)' = \frac{D}{k^{0.5}R}\left(\frac{S_d}{A}\right)^{0.5}$$

This method corrects for change in effective lift:drag ratio during flight by increasing the lift:drag ratio by $10 \times F$ expressed as a percentage.

Finally, the range (in meters) is estimated using:

$$Y = \frac{e\eta}{g}\left(\frac{L}{D}\right)' ln\frac{1}{1-F}$$

Outline method 2 based on Brequet equations.

Method is only appropriate for **non-passerines** and or birds with $bodymass > 50\ g$, lift:drag ratio is calculated at the beginning and at the end of the flight. Lift:drag ratio at the start of flight is calculated using the all-up mass at start, while at end of flight the mass of fuel to be used during the flight it is subtracted from the all up mass. In the function, user can specify percentage of fuel mass to be used during mass. This method, uses the constants defined in method 1.

Step 1 Fat fraction is computed as before (as a ratio of fat mass and all-up body mass).

Step 2 An estimate of the body mass at end of flight is attained by subtracting fuel mass to be consumed during flight from the all-up body mass.

Step 3 Calculate *metabolic power ratio* but this time using body mass at end of flight.

$$X2_{end} = \frac{6.03\ \alpha\ \eta\ \rho^{0.5}\ B^{3/2}M_2^{\delta-5/3}}{k^{3/4}g^{5/3}} \text{where } M_2 = \text{ body mass at end of flight}$$

Profile power constant calculation remains the same as in method 1.

$$X_1 = \frac{C_{pro}}{R_a}$$

Step 4 To find drag at end of flight, metabolic power ratio and the profile power constant are summed and interpolation is done on *table 1* as defined in Pennycuick.

Step 5 Disk area and flat plate area are components that contribute to lift. While disk area is independent of body mass, flat-plate area is not. Therefore, flat-plate area is computed using body mass at end of flight.

$$S_d = \frac{\pi B^2}{4}$$

$$A_{end} = S_b C_{Db} S_b = 0.00813 \times\ m_2^{0.666} C_{Db} = 0.1$$

Where m_2 is body mass at end of flight.

Step 6 Proceed to calculate effective lift:drag ratio at end of flight.

$$\left(\frac{L}{D}\right)'_{end} = \frac{D_{end}}{k^{0.5}R}\left(\frac{S_d}{A_{end}}\right)^{0.5}$$

Step 7 To avoid repetition, Pennycuick demonstrates how to estimate metabolic power constant at start by dividing the estimate at end of flight by some factor.

$$X2_{start} = \frac{X2_{end}}{\left(\frac{1}{1-F}\right)^{7/4}}$$

Followed by interpolation on *table 1* to get drag at start of flight.

Step 8 Get square root of ratio between disk area and flat-plate area at beginning of flight as:

$$\left(\frac{S_d}{A}\right)_{start}^{0.5} = \frac{\left(\frac{S_d}{A}\right)_{end}^{0.5}}{\left(\frac{M_1}{M_2}\right)^{0.5}}$$

Where M_1 and M_2 are all-up mass at beginning and body mass at end of flight respectively.

Step 9 Calculate lift:drag ratio using the start of flight estimates then get the average of the two lift:drag ratio.

Step 10 Get range using the mean of the lift:drag ratio.

$$Y = \frac{e\eta}{g}\left(\frac{L}{D}\right)_{avg}' ln\frac{1}{1-F}$$

Time-marching computation

Breguet equations assume that lift:drag ratio remains constant through out the flight. This is appropriate for fixed wing aircraft. However, birds are known to consume part of the engine (use protein in flight muscles and air-frame as supplementary fuel). This leads to an increase in lift:drag ratio during the flight as result of the reduce in body mass and thus, an increase in flight range [Pennycuick and Battley, 1998]. In the methods discussed above, compensation for this is done by adding 10% of fuel to the lift:drag ratio (method 1) or averaging lift:drag ratio before start of flight and at the end of flight (method 2). Pennycuick and Battley [1998] cites studies which found that protein is replenished faster during short stop-overs compared to fat mass. Furthermore, the constant (e) cannot be assumed to be constant because of two different sources of fuel. Protein and fat have different energy content.

Other than derive equations via ODE, Pennycuick [1998] found it more useful to use the time-marching computation. This simulation assumes that mechanical and chemical powers of a bird are held constant for a short duration during flight (usually 6 minutes), fat and muscle mass are deducted by any one of the three criteria:

- Constant specific work
- Constant specific power
- Constant muscle mass

Pennycuick and Battley [1998] describes time-marching as calculating amounts of fat and protein consumed during a short period (6 minutes) during which all variables including power and speed are assumed constant. After every 6 minute interval, the birds mass composition is revised taking into account the small changes in fat and protein consumed during the interval. In Flight program this is repeated until the required distance it achieved or it runs out of fat mass. This procedure places no restriction on speed. Pennycuick and

Battley [1998] points out that the remaining fat and mass at the end of the flight can be compared with field observations.

The scope of this project involves implementing the time-marching simulation with the constant muscle mass criterion.

Constant Muscle Mass criterion.

Time-marching simulations really on the speed, total mechanical power, and the chemical power.

Speed

The minimum power speed is central in time-marching computation. This is estimated analytically using the formula. Notice it dependent on the air density, and all-up body mass

$$V_{mp} = \frac{0.807k^{1/4}m^{1/2}g^{1/2}}{\rho^{1/2}B^{1/2}S_b^{1/4}C_{Db}^{1/4}}$$

$$V_t = 1.2 \times V_{mp}$$

Total mechanical power

The total mechanical is a sum of three powers:

- **Parasite power**: The rate at which power must be done to overcome drag of body [Pennycuick, 2008]. For any streamlined body the drag is expressed as:

$$D_b = \frac{\rho V_t^2 S_b C_{Db}}{2}$$

And parasite power is found by multiplying the drag by the true airspeed V_t:

$$P_{par} = \frac{\rho V_t^3 S_b C_{Db}}{2}$$

where ρ is the air density, V_t is the true airspeed, S_b is the frontal area of the body and C_{Db} is the body drag coefficient.

- **Profile power** This is power needed to over the effects of the body drag. And this is a multiple of *profile power ratio* (X1) and the absolute minimum power P_{am}:

$$P_{pro} = X1 \times P_{am}$$

$$P_{am} = \frac{(1.05k^{3/4}m^{3/2}g^{3/2}S_b^{1/4}C_{Db}^{1/4})}{(\rho^{1/2}B^{3/2})}$$

and X_1:

$$X_1 = \frac{C_{pro}}{R_a}$$

- **Induced power** Power required to support a birds wight during forward flight.

$$P_{ind} = \frac{(mg^2)}{2V_t Sd\rho}$$

The total mechanical power is found by summing the profile power, parasite power and induced power. Parasite power and induced power are depend on the true airspeed during flight.

$$P_{mech} = P_{pro} + P_{par} + P_{ind}$$

Chemical power

Pennycuick [2008] remarks that mechanical power is derived from measurements made in unaccelerated flight (i.e from forces and speeds that do not involve physiology), however, the chemical power is derived using measurements from physiological experiments. These measurements include:

- Rates of consumption of fuel
- Rate of consumption of oxygen
- Metabolism rate

It is only useful to estimate this in long aerobic flight [Pennycuick, 2008].

To estimate the chemical power during a flight interval, the mechanical power is first estimated (power required from muscles to support the weight against gravity). Then the mechanical power is divided by the mechanical conversion efficiency. A value between 0 and 1, in Flight the default is 0.23. The basal metabolism rate is added because metabolism is a body function that occurs irrespective of what the bird is doing. Estimate derived so far is increased by 10% to account for heart and lungs. This chemical power expresses the total energy required by a bird to sustain flight.

Range Estimation Constant Muscle Mass Criterion

So assembling this mechanism to estimate the flight range, first true airspeed is estimated and used to calculate the total mechanical power, Total mechanical power is converted to chemical power then divided by the energy content of fat (since fat is the only source of fuel in this scenario). Multiplying thhis by the calculation interval (default 6 minutes or 360 seconds) gives the range achieved during this interval in m/s. It was noted that decreasing the flight interval has no effect on range only that the estimation of the processes is more fine grained. This procedure is iterated over until fat mass decreases to zero. In Flight there is an option to attribute a small percentage of the chemical power to protein from the muscle mass, usually 5%

Protein withdrawal criterion.

Pennycuick and Battley [1998] find that holding specific work constant is most realistic criteria for determining how much fuel and protein to be withdrawn during 6 minute intervals of flight. Specific work is defined in as work done by unit mass of contractile tissue muscle. Further, Pennycuick and Battley [1998], states that flight muscles contain myofibrils and mitochondria, which are treated separately in the simulation. To be exact enough mass of myofibrils is reduced by an amount sufficient to restore specific work to the value it had at beginning of flight. In addition, fuel energy corresponding to mass of dry protein consumed is deducted from energy that would otherwise come from fuel/fat consumption. Also, initial climb, and all other flight styles other than continuous wing flapping are not accounted for.

Results comparison.

Note that it is not fair comparison between the methods discused in Pennycuick [1975] and the methods in Pennycuick [2008] and therefore the tables with range estimations are presented separately. Default constants were used for all the observations. Most importantly the air density was set to 1.00 which is about 2000 metres above sea level.

The Data

Data used as an example, is from the program *Flight* for windows [Pennycuick, 2008] version 1.2.5.2. For some observations the fat mass and muscle mass were set to zero, maybe for lack of data since these variables cannot be measured directly compared to the all-up mass and wing span. Flight requires that fat mass is defined to calculate range since it is the main source of fuel. To overcome this, fat mass was randomly generated between 18% and about 35% of the all-up mass (empty mass because crop is empty). For muscle mass, by defualt, Flight uses the muscle fraction 0.17, and therefor this was used to derive the muscle mass.

$$muscle\ fraction = \frac{muscle\ mass}{all - up\ mass}$$

Preset birds from Flight program

Scientific.name

Empty.mass

Wing.span

Fat.mass

Order

Wing.area

Muscle.mass

Anser anser

3.77000

1.600

0.84641

2

0.33100

0.6409000

Hydrobates pelagicus

0.02580

0.355

0.00591

2

0.01610

0.0043860

Pachyptila desolata

0.15500

0.637

0.03886

2

0.04710

0.0263500

Regulus regulus

0.00542

0.156

0.00112

1

0.00525

0.0009214

Calidris canutus

0.12700

0.538

0.03500

2

0.03320

0.0215900

Aegypius monachus

9.90000

3.040

2.02565

2

1.40000

1.6829999

Limosa lapponica

0.36700

0.748

0.20112

2

0.05680

0.0623900

Anas crecca

0.23500

0.582

0.06562

2

0.04580

0.0399500

Hirundo rustica

0.01900

0.318

0.00570

1

0.01320

0.0032300

Cygnus cygnus

12.50000

2.560

2.50000

2

0.75600

2.1250000

Sylvia borin

0.02200

0.240

0.00660

1

0.01100

0.0037400

Luscinia luscinia

0.02700

0.263

0.00675

1

0.01300

0.0045900

Corvus monedula

0.18100

0.600

0.03620

1

0.06180

0.0307700

Anas penelope

0.77000

0.822

0.28607

2

0.08290

0.1309000

Fregata magnificens

1.67000

2.140

0.55799

2

0.37200

0.2839000

Larus ridibundus

0.28500

0.967

0.07881

2

0.09920

0.0484500

Diomedea exulans

9.57000

3.060

2.12836

2

0.64400

1.6268999

Phalacrocorax carbo

2.56000

1.350

0.50768

2

0.22400

0.4352000

Gyps rueppellii

7.30000

2.500

2.52588

2

0.89200

1.2410000

Torgos tracheliotus

6.60000

2.640

2.01454

2

1.03000

1.1220000

Ardeotis kori

11.90000

2.470

3.45889

2

1.06000

2.0229999

Sturnus vulgaris

0.08190

0.384

0.02973

1

0.02530

0.0139230

Fringilla coelebs

0.02300

0.264

0.00690

1

0.01310

0.0039100

Carduelis spinus

0.01120

0.212

0.00336

1

0.00785

0.0019040

Turdus philomelos

0.07160

0.361

0.02148

1

0.02250

0.0121720

Calidris tenuirostris

0.23300

0.587

0.08970

2

0.03960

0.0396100

Buteo swainsoni M

0.77500

1.250

0.22248

2

0.21000

0.1317500

Buteo swainsoni F

1.06000

1.330

0.37117

2

0.24000

0.1802000

Results based on Pennycuick [1975]

```r
results_fixed_wing <- flysim(data = birds)
```

```
## ## settings not defined. Using default constants.
##
## Default airDensity = 1.00 kg m^3
```

```r
# range
results_fixed_wing$range
```

```
##          Anser anser  Hydrobates pelagicus   Pachyptila desolata
##               3193.8                3252.9                4192.0
##      Regulus regulus      Calidris canutus     Aegypius monachus
##               1521.6                4240.6                3951.6
##     Limosa lapponica           Anas crecca       Hirundo rustica
##              11209.3                3631.4                3898.0
##        Cygnus cygnus          Sylvia borin     Luscinia luscinia
##               3296.0                2801.7                2301.9
##      Corvus monedula         Anas penelope  Fregata magnificens
##               2452.7                5428.0               10527.4
##     Larus ridibundus      Diomedea exulans   Phalacrocorax carbo
##               5847.5                5436.8                2918.8
##      Gyps rueppellii   Torgos tracheliotus          Ardeotis kori
##               6808.3                6334.7                4211.5
##     Sturnus vulgaris     Fringilla coelebs      Carduelis spinus
##               4197.4                2867.9                2926.6
##    Turdus philomelos Calidris tenuirostris     Buteo swainsoni M
##               3025.5                6053.5                5422.5
##    Buteo swainsoni F
##               6994.8
```

```r
# constants used
results_fixed_wing$constants
```

```
##         ppc        eFat    eProtein           g         mce         ipf
##    8.40e+00    3.90e+07    1.80e+07    9.81e+00    2.30e-01    1.20e+00
##         vcp  airDensity         bdc      alpha1      alpha2      delta1
##    1.10e+00    1.00e+00    1.00e-01    6.25e+00    3.79e+00    7.24e-01
##      delta2    invPower  speedRatio muscDensity         phr
##    7.23e-01    1.20e-06    1.20e+00    1.06e+03    2.20e+00
```

Time-marching: Constant Muscle Mass

In the simulation in Flight program, air density was set to 1 (Altitude 2063 meters above sea-level), muscle was held constant (Protein burn criterion), fat energy at $3.9E+07$, continuous flapping style (Flight style), and minimum energy from protein at 0% instead of the defualt 5%. Induced power factor is set to 1.20 for all birds. The mitochondrial fraction is set to hold constant.

Flight provides two methods of speed control, true air-speed to minimum power speed is held constant or true air-speed is held constant. Both of these scenarios are compared to the output of this package below:

```r
# constant speed
results_cmm_cs <- migrate(data = birds, speed_control = "constant_speed")
```

```
## ## settings not defined. Using default constants.
##
## Default airDensity = 1.00 kg m^3
```

```r
results_cmm_cs$range
```

```
##           Anser anser  Hydrobates pelagicus   Pachyptila desolata
##              3090.212              2670.168              3697.655
##       Regulus regulus      Calidris canutus     Aegypius monachus
##              1112.737              3815.854              3510.380
##      Limosa lapponica           Anas crecca      Hirundo rustica
##             11422.128              3388.011              2922.039
##         Cygnus cygnus          Sylvia borin     Luscinia luscinia
##              3093.674              2251.541              1867.620
##       Corvus monedula         Anas penelope   Fregata magnificens
##              2030.797              5192.960              9892.096
##      Larus ridibundus      Diomedea exulans   Phalacrocorax carbo
##              5311.779              5505.702              2606.114
##       Gyps rueppellii   Torgos tracheliotus         Ardeotis kori
##              6437.457              5791.601              3914.659
##      Sturnus vulgaris     Fringilla coelebs      Carduelis spinus
##              3570.048              2384.724              2221.557
##     Turdus philomelos Calidris tenuirostris     Buteo swainsoni M
##              2688.390              5657.302              5076.476
##     Buteo swainsoni F
##              6432.601
```

```r
# constant ratio between true air-speed and minimum power speed
results_cmm_cratio <- migrate(data = birds, speed_control = "vvmp_constant")
```

```
## ## settings not defined. Using default constants.
##
## Default airDensity = 1.00 kg m^3
```

```r
results_cmm_cratio$range
```

```
##           Anser anser  Hydrobates pelagicus   Pachyptila desolata
##              3007.666              2585.928              3578.702
##       Regulus regulus      Calidris canutus     Aegypius monachus
##              1076.763              3684.099              3424.932
##      Limosa lapponica           Anas crecca      Hirundo rustica
##             10656.723              3267.217              2789.200
##         Cygnus cygnus          Sylvia borin     Luscinia luscinia
##              3016.846              2147.015              1798.886
##       Corvus monedula         Anas penelope   Fregata magnificens
##              1975.244              4952.667              9508.971
##      Larus ridibundus      Diomedea exulans   Phalacrocorax carbo
##              5124.442              5378.213              2548.818
##       Gyps rueppellii   Torgos tracheliotus         Ardeotis kori
##              6146.924              5559.672              3756.543
##      Sturnus vulgaris     Fringilla coelebs      Carduelis spinus
##              3378.812              2275.475              2119.291
##     Turdus philomelos Calidris tenuirostris     Buteo swainsoni M
```

```
##              2571.456              5381.771              4887.604
##     Buteo swainsoni F
##              6142.628
```

Comparison table constant speed

package_cons_speed

flight_cons_speed

Anser anser

3090.212

3090

Hydrobates pelagicus

2670.168

2670

Pachyptila desolata

3697.655

3702

Regulus regulus

1112.737

1115

Calidris canutus

3815.854

3821

Aegypius monachus

3510.380

3519

Limosa lapponica

11422.128

11418

Anas crecca

3388.011

3383

Hirundo rustica

2922.039

2922

Cygnus cygnus

3093.674

NA

Sylvia borin

2251.541

2248

Luscinia luscinia

1867.620

1867

Corvus monedula

2030.797

2031

Anas penelope

5192.960

5186

Fregata magnificens

9892.096

9880

Larus ridibundus

5311.779

5308

Diomedea exulans

5505.702

5498

Phalacrocorax carbo

2606.114

2606

Gyps rueppellii

6437.457

6439

Torgos tracheliotus

5791.601

5776

Ardeotis kori

3914.659

NA

Sturnus vulgaris

3570.048

NA

Fringilla coelebs

2384.724

2385

Carduelis spinus

2221.557

2221

Turdus philomelos

2688.390

2684

Calidris tenuirostris

5657.302

5658

Buteo swainsoni M

5076.476

5071

Buteo swainsoni F

6432.601

6427

Comparison table constant speed ratio

package_cons_ratio

flight_cons_ratio

Anser anser

3007.666

3007

Hydrobates pelagicus

2585.928

2586

Pachyptila desolata

3578.702

3566

Regulus regulus

1076.763

1076

Calidris canutus

3684.099

3679

Aegypius monachus

3424.932

3417

Limosa lapponica

10656.723

10647

Anas crecca

3267.217

3267

Hirundo rustica

2789.200

2789

Cygnus cygnus

3016.846

3016

Sylvia borin

2147.015

2146

Luscinia luscinia

1798.886

1798

Corvus monedula

1975.244

1975

Anas penelope

4952.667

4946

Fregata magnificens

9508.971

9499

Larus ridibundus

5124.442

5120

Diomedea exulans

5378.213

5378

Phalacrocorax carbo

2548.818

2541

Gyps rueppellii

6146.924

6140

Torgos tracheliotus

5559.672

5544

Ardeotis kori

3756.543

NA

Sturnus vulgaris

3378.812

3374

Fringilla coelebs

2275.475

2275

Carduelis spinus

2119.291

2119

Turdus philomelos

2571.456

2571

Calidris tenuirostris

5381.771

5381

Buteo swainsoni M

4887.604

4871

Buteo swainsoni F

6142.628

6153

Future work

In this section, aim is to discuss the evolution path of the package so that it incorporates as many features from Flight program as possible. ## Protein withdrawal criterion Pennycuick and Battley [1998] find that holding specific work constant is most realistic criteria for determining how much fuel and protein to be withdrawn during 6 minute intervals of flight. This is in comparison with field observations. Specific work is defined in as work done by unit mass of contractile tissue muscle. Further, Pennycuick and Battley [1998], states that flight muscles contain myofibrils and mitochondria, which are treated separately in the simulation. To be exact enough mass of myofibrils is reduced by an amount sufficient to restore specific work to the value it had at beginning of flight. In addition, fuel energy corresponding to mass of dry protein consumed is deducted from energy that would otherwise come from fuel/fat consumption.

Holding the specific power constant is a third option in Flight program. In this scenario, just enough protein from muscle mass is used to maintain the specific power estimated at beginning of flight.

Supplemtary protein from air-frame

In Flight program user has an option to specify minimum percentage of energy that should come from protein. It is possible that muscle mass alone would not be able sustain this, and therefore some of the protein can come from the air-frame.

Initial climb

Initial climb, calculates the power required by the bird at start of flight. It is possible that a bird maybe to heavy to fly under some conditions. In Table 3 and 4 there were such cases.

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