Dragon Flight Analyzer

A fuzzy logic system to determine if, and how well, a dragon might be able to fly

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Introduction

Dragons—in particular the winged lizard-like "western dragons"—are enduringly popular creatures in fantasy media, despite the many implausible features dragons are portrayed as having. Some artists and viewers, as well as writers and readers, are content to allow the impossible into their fantasy. These people might propose magic or different physical laws as explanations, or else simply accept inconsistencies.

However, there are plenty of fantasy lovers who like fantasy elements to have some sort of potential logic, not content with what *cannot* exist if they can instead have what merely *does not* exist. Creators and consumers might (and sometimes do) ask: What physical mechanisms could allow a dragon to breathe fire? What skeletal arrangement could allow a vertebrate to have six functional limbs? And, as we will be discussing in this paper, could an enormous, scaly, toothy reptile actually fly?

How to Fly

The most basic question about a dragon is whether its wings are large enough to permit flight. Even a rudimentary understanding of aeronautics tells us that a creature's wings need to be big enough to support its weight, or it will fall out of the sky. Put more precisely, the ratio of an animal's mass to the total area of its wings is the significant factor. This measure of mass/area is called *wing loading*, and will be one of our two main measures for analyzing the ability of a dragon to fly. Wing-loading figures for flying animals such as birds are often reported as grams per square centimeter, kilograms per square meter, or (using weight rather than mass) as newtons per square meter. In this paper, all wing-loading values will be stated in terms of kg/m^2.

So, what does wing loading tell us about whether a dragon can fly? There's no immediately obvious figure for wing loading that's "too big". Large airplanes can fly with wing loadings of hundreds of kilograms per square meter. A Boeing 747 has a wing loading of around 730 kg/m^2, for example (Science Learning Hub, 2011).

It turns out the effectiveness of the wings for a given wing loading is dependent on how quickly the creature or object is flying: the faster you fly, the more wing loading you can endure. Naturally, powerful aircraft engines can deliver a lot more speed than the muscles of a flapping animal. A frequently cited analysis suggests the maximum wing loading for a bird to fly is around 25 kg/m^2 (Meunier, 1951). While a dragon is obviously not a bird, we can consider big, heavy birds like albatrosses and swans as the closest approximations alive today to tell us how large vertebrates might be able to fly.

This means we have our simple answer for whether a dragon can fly. Determine its wing loading, and if that is within 25 kg/m², then it can fly. However, if we're going to all the trouble of computing a fictional creature's mass and the area of its wings, it would be nice to get more than just a yes/no for its flight capabilities. Can it fly quickly? Can it maneuver in flight? How hard does it have to work to stay in the air? To answer these questions, we're going to go back to birds and look at the influence that both wing size and wing shape have on how they fly.

How to Fly Well

While there are many factors that contribute to exactly how a bird flies—aerodynamics of the body, exact contours of the wings, length of the tail, and other factors—we want to stay within the realm of reasonable calculation. Building a scale model of a dragon we want to test, giving it realistic texturing and putting it into a wind tunnel to test its aerodynamic properties seems to be going a bit far for analyzing the capabilities of a fictional creature. Fuzzy logic is perfect for this task, since using a fuzzy rule set will allow us to sidestep the precise and extremely detailed analysis we would otherwise need.

However, we need more than just wing loading to build our rule set. There is another measure of a bird's wings that is very powerful for explaining how one bird's flight differs from that of another bird: aspect ratio.

The aspect ratio of a bird's wings is a measure of how long they are compared to the width, or "chord", of the wings. A high-aspect ratio means the wings are long and narrow (like those of an albatross), while a low-aspect ratio means broader and relatively shorter wings (like a crow's). Birds with high-aspect ratio wings tend toward a soaring style of flight, with their wings held out straight, while low-aspect ratios are associated with more flapping. There are a few ways to measure aspect ratio, but for this this paper, we will use the square of wingspan, divided by the area of the wings. Given that this is m²/m², aspect ratio is therefore a unitless measure.

Together with wing loading, aspect ratio allows us two axes on which to characterize the flight capabilities of a bird. Birds' wings are often grouped into four different types, with different characteristics, as follows (Saville, 2006):

- Elliptical wings: short and rounded, offering high maneuverability and good for rapid takeoffs from the ground. Example birds: crows, pheasants (and most bats as well).
- High-speed wings: short and pointed, offering high top speed at the cost of fast, tiring flapping. Example birds: falcons, ducks.
- High-aspect ratio wings: long and pointed, offering efficient soaring, especially when flying in the strong dynamic winds that occur over water. Example birds: albatrosses, gulls.

- High-lift wings: long and broad, with deep slots between feathers, offering slow soaring with good but not outstanding maneuverability. Example birds: eagles, vultures.

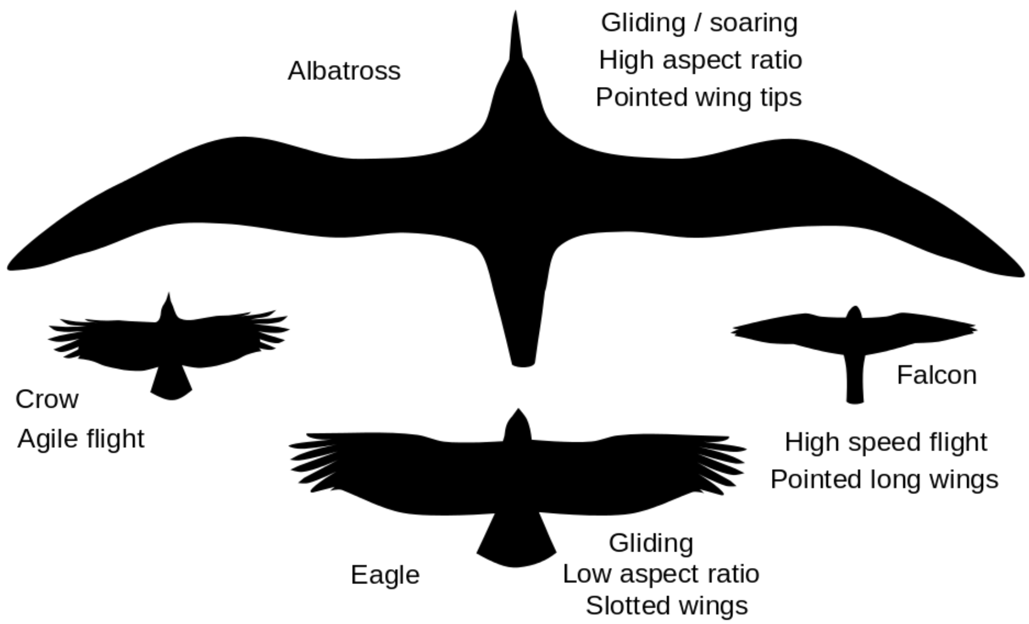


Figure 1: Silhouettes of the four main shapes of bird wings. Image by L. Shyamal, shared under the CC-BY-SA-2.5 license.

Using our two measures of wing loading and aspect ratio, we can see that these four types of wings approximate the four corners of a grid:

- Elliptical wings: low-aspect ratio, low wing loading
- High-speed wings: low-aspect ratio, high wing loading
- High-aspect ratio wings: high-aspect ratio, high wing loading
- High-lift wings: high-aspect ratio, low wing loading

These characteristics are very useful in creating the rules for our fuzzy logic system. But before we dive into fuzzy rules, we need to be able to estimate our dragon's wing loading and aspect ratio.

Statistics Time

We start with the givens for our dragon. The three values we need in order to calculate its flight capabilities are wingspan, wing area, and mass. What input will allow us to find these measures?

Wingspan is easy. Since we need to set wing length anyway, to test different sizes of dragons, wingspan should be one of our starting parameters.

Wing area is somewhat more involved. Wingspan is close to being the combined length of the wings, but we have to add in the width of the torso. While the width of the dragon's torso could be a parameter, we already know we want the dragon's body to be lizard-like, since that's the western-style dragon, the kind we're analyzing. While different lizards have different degrees of skinniness, we want to be consistent about torso width, since it's the effectiveness of the wings we want to analyze. We do want to be able to run the analysis for different overall sizes of dragons, though, so the dragon's length will be a parameter, using a consistent torso width to length ratio.

To develop a torso width to overall length ratio, we need a suitable lizard model. We want a large lizard, since our analysis is all about what kind of wings a *big* animal needs to be able to fly. The obvious lizard to use, of course, is the heaviest lizard in the world: the Komodo dragon. (The name is a nice bonus.) Looking at photos of Komodos and measuring with a ruler, the torso appears to be around one-tenth the length of the entire body, including the tail. The length of each wing, therefore, will be: (wingspan - (body length)/10) / 2.

Finally, to calculate the area of the wings, we need a measure of their width. Unlike the width of the torso, we must be able to adjust the width, or chord, of the wings, since aspect ratio is one of the factors we are considering for dragons' flight capabilities. We will therefore add wing chord as a third starting parameter to describe our dragon.

If wings were rectangles, this would be enough: we would simply calculate the area of the wings as length*chord. However, since wings are not rectangular, our calculation needs to reflect actual wing shape. As we know, different bird species have different wing shapes, but just as we have decided on a consistent torso width to reduce unnecessary variability, we will do the same for wing shape. Two possible calculation approaches come to mind:

- Treat each wing as though it is a rectangle close to the body, and a triangle at the tip. This is a good approximation of both high-speed wings and high-aspect ratio wings. The area of such a wing is length*chord + length*chord*1/2 = length*chord*3/4.
- Treat each wing as though it is a quarter-section of an ellipse. This is a good approximation of elliptical wings and high-lift wings. The area of such a wing is length*chord*π/4.

Given that pi is close to 3, these formulae are roughly approximate to each other, making it unnecessary to use different calculations for different sorts of wings. Since we are interested in making sure our dragon's wings are large enough to allow flight, we will err on the side of caution and take the lower estimate: three-quarters of length times chord.

Finally, we need the mass of our dragon. We have already decided to use a Komodo dragon as our model, so we need the length-to-mass conversion rate for Komodos. A large male Komodo dragon is about 3 meters long. In the comfort of captivity, one Komodo reached 166 kilograms, but a more typical lean, mean wild Komodo is around 70 kilograms (Smithsonian's

Natural Zoo & Conservation Biology Institute, 2016). The cube root of 70 is about 4.12, which, divided by 3, gives us a calculation of approximately $(1.37*\text{length})^3$; 1.37 is close to being the square root of 2 (1.41), which seems like a convenient bit of rounding up to account for any extra weight due to the bodily attachment for wings.

That settles the mass of the body, but wing mass needs to be accounted for as well. Unlike the simple cubic rule to get from body length to mass, it's not obvious how scaling from smaller to larger wings will increase the mass of the wings. In theory, the mass of the wing must at least increase proportionally to the area. However, using linear scaling does not account for the bones and muscles becoming thicker from bottom to top to support the added wing volume.

Does that mean we should assume the thickness of the wings increases in lockstep with the width and length, giving an estimated scaling factor of $(\sqrt{\text{area}})^3 = \text{area}^{1.5}$? Probably not. While the bone- and muscle-dense front of the wing will increase in weight rapidly, the thin trailing edge will increase far less, because the thickness of wings tapers toward the back edge. Additionally, since the strength of bone is in large part proportional to its cross-sectional area (Nelson, Barondess, Hendrix, & Beck, 2000), just as the strength of muscle increases in proportion to its cross-sectional area (Jones, Bishop, Woods, & Green, 2008), increasing the width of the wing will increase the strength of both bone and muscle. We should therefore expect somewhere between quadratic (area^1) and cubic ($\text{area}^{1.5}$) scaling. For simplicity, let's set the exponent halfway between, making it $\text{area}^{1.25}$.

To finish our estimate of wing mass, we need the appropriate constant factor to go along with our 1.25 exponent, just as body mass has a constant factor of $\sqrt{2}$. For this, I used published lists of actual wing areas and wing masses of various species of birds and bats (Van den Berg & Rayner, 1995; Shyy, Aono, Kang, & Liu, 2013). These two sources combined provided statistics for 43 species of birds and 10 species of bats, which I compiled and ran through linear regression ($x^{1.25}$ regression would have been ideal, but was not available in my statistical tool, and for these low-mass animals the result will be extremely similar in any case).

This produced a very strong regression with statistical p-value of <.001, giving a regression factor of 1.419. This is reassuringly close to our earlier use of $\sqrt{2}$, and I will use that approximation again for simplicity.

To summarize the above, our analysis tool has three input parameters:

- Body length
- Wingspan
- Wing chord

And from these, we compute wing loading and aspect ratio as follows:

- Wing area = (wingspan - (body length)/10) * wing chord * 0.75
- Mass = $(\sqrt{2} * \text{body length})^3 + (\sqrt{2} * \text{wing area})^{1.25}$
- Wing loading = mass / wing area
- Aspect ratio = wingspan^2 / wing area

With these formulae established, we are ready to design our fuzzy logic system to use these formulae to compute wing loading and aspect ratio values to tell us whether and how well our dragon could fly.

Rule of Fuzz

Earlier, we defined the four types of bird wings (elliptical, high speed, high aspect ratio, and high lift) in terms of expected wing loading and aspect ratio characteristics:

- Elliptical wings: low-aspect ratio, low wing loading
- High-speed wings: low-aspect ratio, high wing loading
- High-aspect ratio wings: high-aspect ratio, high wing loading
- High-lift wings: high-aspect ratio, low wing loading

Now that we have calculated wing loading and aspect ratio, these will form the basis of our fuzzy rule set.

What do these four categories mean for flight characteristics? We are especially interested in how fast our dragon can fly (*Speed*), how long it can fly before getting tired (*Efficiency*), and how easily it can take off, land, and steer in the air (*Maneuverability*). Van den Berg and Rayner, and Shyy et al also provide information on flight characteristics.

Elliptical wings are helpful to steer around obstacles and take off quickly to avoid predators, giving them a high maneuverability rating. However, the rapid flapping of short wings is tiring (low efficiency), and these wings are not particularly fast (medium speed).

High-speed wings, as their name indicates, provide high speed. They are functionally as tiring as elliptical wings, if not more so (low efficiency), and the higher wing loading reduces maneuverability somewhat (medium maneuverability).

High-aspect ratio wings, such as those on soaring sea birds, provide high efficiency. They are not particularly fast wings (medium speed), and the combination of high-aspect ratio and high wing loading makes birds like albatrosses famously poor at efficient takeoff and landing (low maneuverability).

High-lift wings are also used for soaring, and, like high-aspect ratio wings, they provide high efficiency. The sheer size of the wings gives a low speed, but maneuverability is improved over high-aspect ratio wings by the lower wing loading (medium maneuverability).

Our current rule set looks something like this:

1. Low-aspect ratio & low wing loading = medium speed, low efficiency, high maneuverability
2. Low-aspect ratio & high wing loading = high speed, low efficiency, medium maneuverability
3. High-aspect ratio & high wing loading = medium speed, high efficiency, low maneuverability
4. High-aspect ratio & low wing loading = low speed, high efficiency, medium maneuverability

This is a good start, but there are two problems. First, we're missing a rule to deal with cases when wing loading is too high to allow flight ("extreme" wing loading). This can be solved by making a new rule saying that extreme wing loading, regardless of aspect ratio, indicates zero speed, zero efficiency, and zero maneuverability.

Second, except for extreme wing loading, aspect ratio and wing loading are expressed only in terms of high and low, while our flight characteristics have low, medium, and high. Surely, though, it's possible to have a medium aspect ratio, and a medium wing loading. While a rating of medium, or average, could simply be assigned to the midpoint where low and high meet, it seems preferable to be able to say that a wing is functionally average in either of the measures. This also has the advantage of making our rule more accurate by making these measures applicable to aspects of functioning.

For example, high-aspect ratio wings are, of course, associated with a high-aspect ratio, but not necessarily with high wing loading. Some smaller species of albatross have more moderate wing loading. Birds with high-lift wings, meanwhile, sometimes have more moderate aspect ratios than high, because extremely long wings can make nesting difficult. This applies to many eagles, for example, which have shorter wings than their high-aspect ratio would seem to indicate. Elliptical wings can be strained to moderate wing loading by larger birds like pheasants, which benefit from flying quickly for short distances, while high-speed wings can have a more moderate aspect ratio for birds like swifts that benefit from staying in the air longer (Witton & Habib, 2010; Savile, 2006; Henningsson, Hedenström, & Bomphrey, 2014; among others).

Establishing medium-aspect ratio and medium wing loading allows us to make those distinctions. It also produces the intermediate "unspecialized" category of wings for medium-aspect ratio and medium wing loading, which will help reduce swings between extremes that might otherwise be caused by relatively small adjustments.

Putting all this together, our fuzzy rule set contains 6 rules:

Aspect Ratio	**Wing Loading**	**Wing Type**	**Speed**	**Efficiency**	**Maneuverability**
Low	¬High, ¬Extreme	Elliptical	Medium	Low	High
!High	High	High Speed	High	Low	Medium

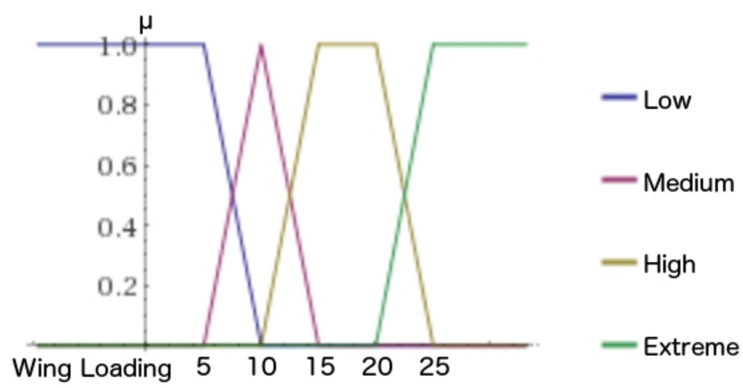
High	¬Low, ¬Extreme	High Aspect Ratio	Medium	High	Low
!Low	Low	High Lift	Low	High	Medium
Medium	Medium	Unspecialized	Medium	Medium	Medium
—	Extreme	Flightless	None	None	None

The last step before our system is ready for use is to figure out what membership values correspond to these fuzzy categories.

What is the Fuzziest Number That You'll Ever Know?

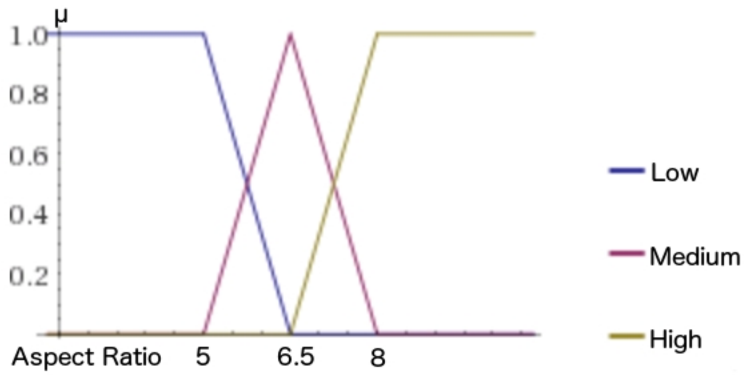
We already have our answer for what an "extreme" wing loading is, numerically: 25 kg/m². However, some research is needed to determine where to set the boundaries for low, medium, and high.

According to *Energetics of Flight* (Norberg, 1996), wing loading for birds ranges from about 1.73 kg/m² (small hummingbirds) to 23.45 kg/m² (whooper swans). Bats have low wing loading compared to birds, and Neuweiler (2000) presents a graph showing bat wing loading ranging from about 0.3 to 3 kg/m². Finally, Witton and Habib (2010), in a chart showing the wing loading of various sea birds, reveal that giant petrels and some large species of albatross range upward to about 15 kg/m², while medium-size albatrosses range down to around 10 kg/m².



Taken together, these values suggest that a "high" wing loading value should be fairly broad, ranging from around 10 to 25 kg/m². This wide range makes sense, since many birds need to be able to fly while carrying objects or after eating a large meal, which increases their mass, and therefore their wing loading. Some birds with relatively high wing loadings will therefore still be well below their wings' theoretical maximum weight. The remaining wing loading categories can be filled in simply by putting the centre of "medium" wing loading at 10, and the upper inflection point of "low" at 5.

For aspect ratio, Norberg (1996) notes that aspect ratio varies from 4 to 18 across bird species. For more detail on exactly where to cut the break points, Savile (2006) says that elliptical wings tend toward an aspect ratio of 4.5-6, high lift wings around 6-7 or higher, and high aspect ratio wings from 8 and up.

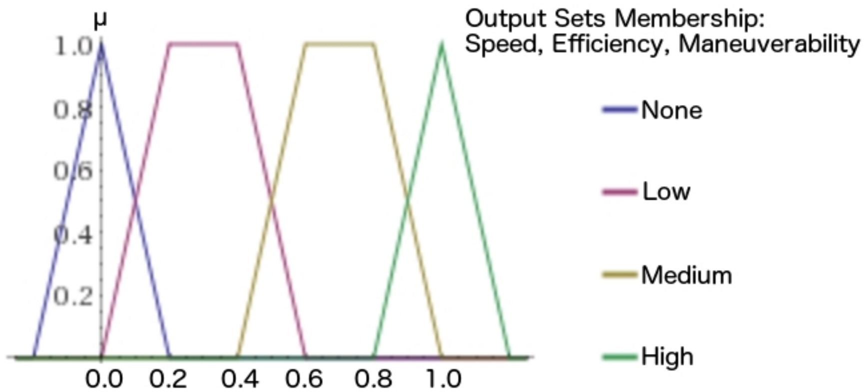


Given that low-aspect ratio elliptical wings and medium-to-high-aspect ratio high-lift wings meet at around 6, we should expect an aspect ratio of 6 to be moderately low, meaning it falls between the upper inflection point of low and the peak of medium. Placing the peak of "medium" right in the middle of the 6-7 range for relatively short-winged high-lifters accomplishes this nicely. Meanwhile, 8 seems to be the start of the zone where an aspect ratio is entirely in the high range. If the intersection range of medium and high aspect ratio is 6.5-8, then we might as well make the "medium" triangle symmetrical, placing our upper inflection point for "low" aspect ratios at 5.

Finally, we need to determine the fuzzy operators we're using for our rules, and how the consequents of the rules transfer to membership in our three output sets: Speed, Efficiency, and Maneuverability.

First, we need an "and" operator. We have no specific needs to satisfy, so we can simply use minimum. Second, we need negation, for which standard negation will suffice. Third, we need an "or" operator. In this case, we do have a particular need, because of the rule for how elliptical wings work. Using maximum won't work, because we need the membership value of 22.5 kg/m² to be 1.0 for the statement !(High or Extreme). Instead, with maximum, we will use 0.5. Since we have arranged our membership values above, such that the total membership value across all categories will be 1.0 for any wing-loading value, we are able to use an unusual "or" operator: arithmetic sum. In the range we need to be equal to 1.0, High+Extreme will always be 1.0, whereas if High and Medium are partially true, then Extreme will be 0.0 and the membership of High+Extreme will simply equal High.

We now have everything we need to determine the degree to which each of our fuzzy rules is true. The last step is to pull the consequents together to determine membership in our three output sets. The Mean of Maxima method is unsuitable, because we don't want to ignore any non-maximal results. Even if our dragon's wings are only a little like elliptical wings, we still want that to be reflected in our output. Instead, the Center of Mass method is suitable, since it allows us to easily let all rules influence the fuzzy outputs. If we use scaling rather than clipping, and ensure our output membership categories are all symmetrical, then computing the centre of mass is simply a matter of multiplying the consequent of each rule by the median value of the output category, summing across all rules, and dividing by the cardinality of the set of consequents.



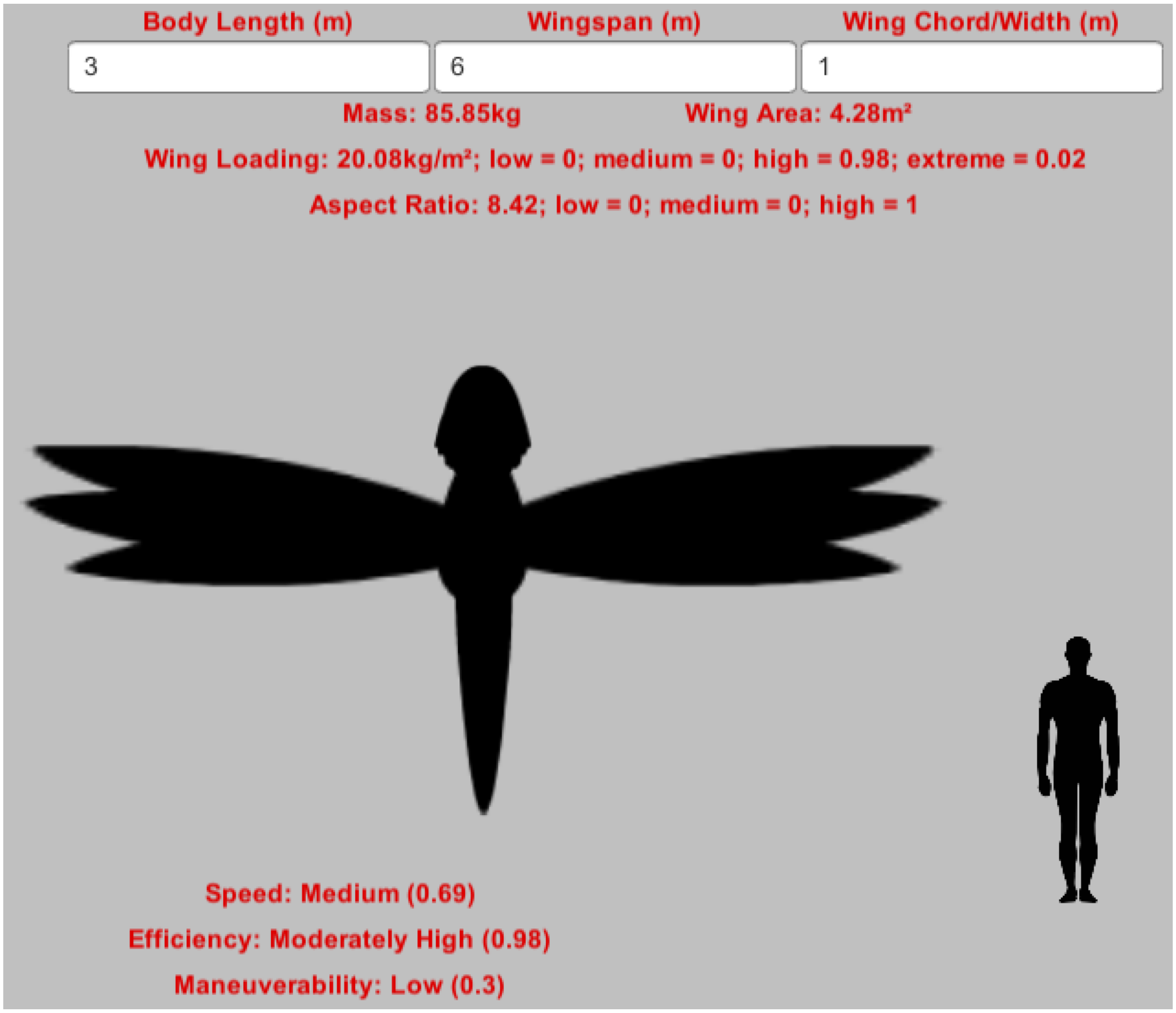
In terms of the membership categories of the fuzzy outputs, each of them is divided into four categories: high, medium, low, and (for the extreme wing-loading rule) none. Finding the centres of high and none is easy: simply place them at 1.0 and 0.0 respectively. For the remainder, there are effectively five other gradations. In addition to "low" and "medium", there are also the crossover zones between none and low ("very poor"), low and medium ("moderately low"), and medium and high ("moderately high"). Placing the peaks of low and medium at 0.3 and 0.7, respectively, affords an equal share to each of these zones, which is mathematically tidy. "None" and "high" are defined as triangles so they will be symmetrical, as described in the previous paragraph, though of course in practice, there will never be a membership value lower than 0.0 or higher than 1.0.

Since we want to avoid the huge number of factors that go into calculating actual numbers for the outputs, we will not defuzzify them. It's quite sufficient to have a membership value of how fast, how efficient, and how maneuverable our dragon's flight is.

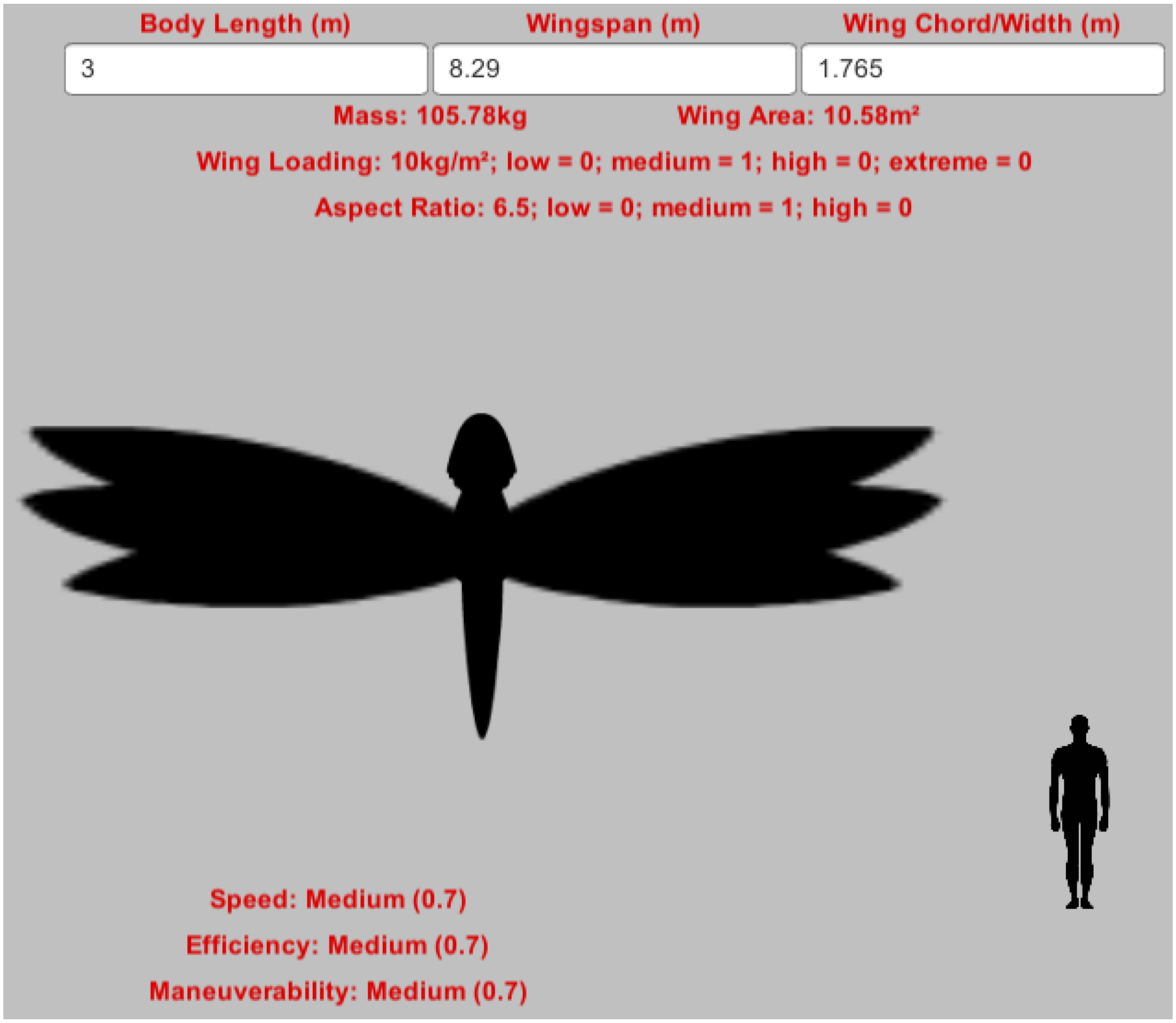
Basing the classic western-style dragon on elements of bird and lizard physiology, this paper uses fuzzy logic to prove that dragons would be capable of flight. While larger-winged dragons are more aerodynamically feasible than the large-bodied smaller-winged dragons sometimes depicted, the shape of the wing and desired flight characteristics are also key variables, so that the feasibility of dragon flight does not come down to a wing size–body mass ratio alone. For those viewers and readers of fantasy whose suspension of disbelief can be dangled only so far, this is welcome information. After all, as J.R.R. Tolkien said in *The Hobbit*, "It does not do to leave a live dragon out of your calculations, if you live near him."

Example

Suppose we have a dragon the size of a Komodo dragon, at 3m long. How large should the wings be? We start with some simple numbers: suppose 3m body length, 6m wingspan, 1m wing chord. Can this dragon fly?



Yes, it can. However, the wing loading is bordering on extreme. Our poor dragon is one large meal away from being grounded. Let's increase the wingspan and wing chord a bit, to give a little more leeway.



That's better. With an 8.29m wingspan and 1.765m wing chord, our dragon can fly easily on unspecialized wings. Tweaks in any direction can give our dragon any of the four main wing types. Lowering the wing chord, for example, will increase both wing loading and aspect ratio, edging the dragon toward high-aspect ratio wings that are good for soaring. Decreasing the wingspan, meanwhile, will lower the aspect ratio while increasing wing loading, helping move the dragon toward high-speed wings.

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