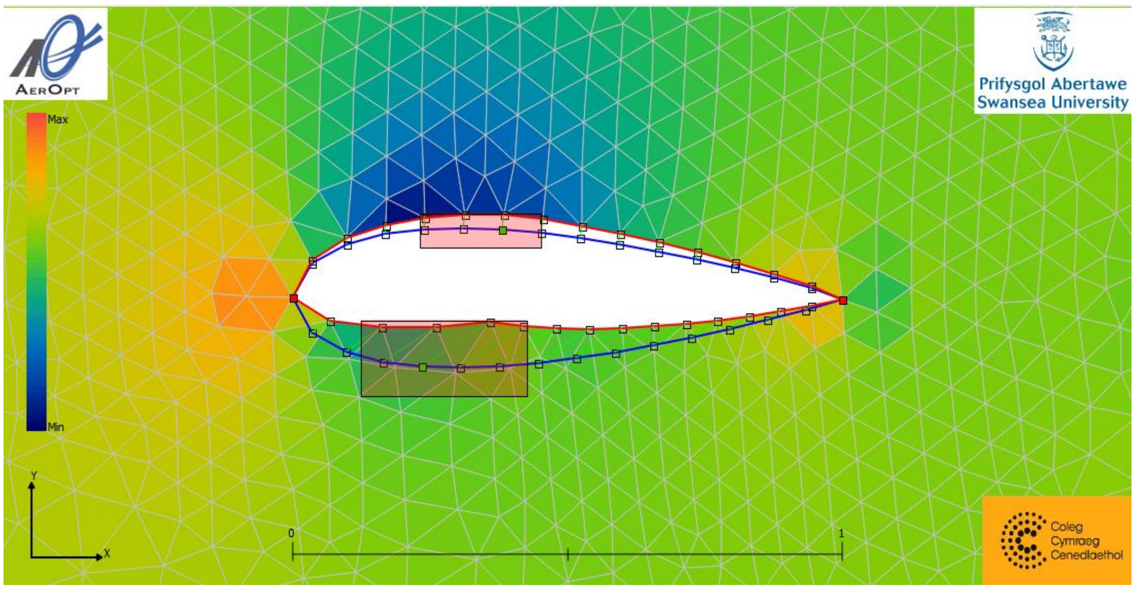
AEROPT USER MANUAL



version 1.1

AerOpt – Aerodynamic Optimisation Software

This document is a user guide for the interactive aerodynamic optimisation software *AerOpt* developed at Swansea University's College of Engineering

AEROPT user manual

AEROPT – AERODYNAMIC OPTIMISATION SOFTWARE

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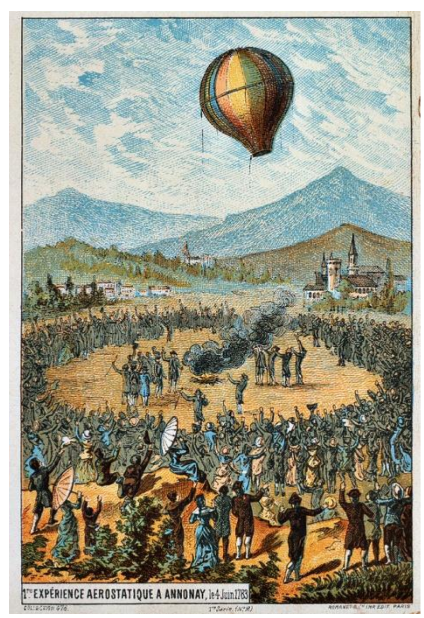
1) What is Aerodynamic Optimisation?

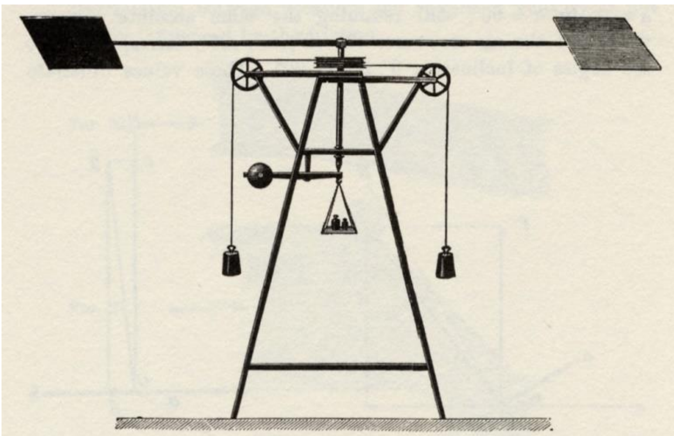
Ever since humans looked to the skies and marvelled at the elegant freedom of birds in flight we have been wondering about how to design machines that fly. Da Vinci famously developed designs for a flying machine 500 years ago and in the 18th Century the first 'lighter than air' manned flight took place using a hot air balloon.



Da Vinci's 'Ornithopter' flying machine

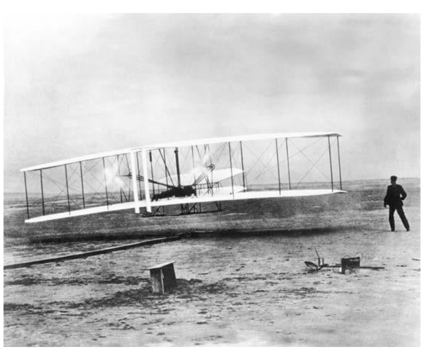
First public hot air balloon demonstration by the Montgolfier brothers, 4 June 1783

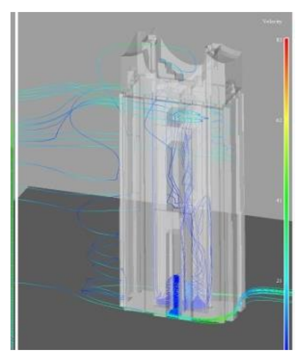
It wasn't until the 'Grandfather of Aeronautics', Sir George Cayley started experimenting with a 'whirling arm' in the late 18th Century that we began to develop an understanding of what happens as air flows over bodies like birds, aeroplanes, cars or anything, for that matter! This field of science became known as aerodynamics.



PICTURE: Cayley's Whirling Arm (SU)

The Wright Brothers famously achieved the first powered flight in 1903 and since then aerodynamicists have been on a perpetual quest to improve the design of aircraft and, specifically, their wings. Nowadays you will find aerodynamicists working everywhere, from aircraft companies like Airbus and Boeing and Formula 1 teams (who use aerodynamics to generate downforce) to the companies designing large structures such as skyscrapers and bridges.





The aerodynamic designer is anyone who is designing something (be it a car, aeroplane, bridge or building) to take advantage of the aerodynamics. The process of design often involves lots of trial and error (or 'design iterations') and this design process, especially if it is automated, is referred to as 'optimisation'.

AerOpt is a software package being developed by research engineers at Swansea University. This document is a user guide for the schools' version of the software.

2) Theory – how does it work?

Computational Fluid Dynamics (CFD)

Most engineering fluid flow problems are now solved, at least in part, by means of Computational Fluid Dynamics, or 'CFD' for short. This is the use of computers in the solution of the complicated equations of fluid dynamics. The mathematical equations for the majority of practical fluid flow problems are Partial Differential Equations, or PDEs, as is the case for many naturally occurring phenomena. The set of equations that are most relevant for describing the aerodynamic flows are the 'Navier-Stokes' equations. These are a set of 5 PDEs describing quantities such as the density, velocity and pressure of the airflow. To give some idea of the degree of complexity of this set of equations, they are shown in the figure below:

$$\frac{\partial \varrho}{\partial t} + \frac{\partial (\varrho u)}{\partial x} + \frac{\partial (\varrho v)}{\partial y} + \frac{\partial (\varrho w)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial (\varrho u)}{\partial t} + \frac{\partial \left(\varrho u^2\right)}{\partial x} + \frac{\partial (\varrho u v)}{\partial y} + \frac{\partial (\varrho u w)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial (\varrho v)}{\partial t} + \frac{\partial (\varrho v u)}{\partial x} + \frac{\partial \left(\varrho v^2\right)}{\partial y} + \frac{\partial (\varrho v w)}{\partial z} = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\frac{\partial (\varrho w)}{\partial t} + \frac{\partial (\varrho w u)}{\partial x} + \frac{\partial (\varrho w v)}{\partial y} + \frac{\partial \left(\varrho w^2\right)}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$\frac{\partial (\varrho \varepsilon)}{\partial t} + \frac{\partial (\varrho \varepsilon u)}{\partial x} + \frac{\partial (\varrho \varepsilon v)}{\partial y} + \frac{\partial (\varrho \varepsilon w)}{\partial z} = -\frac{\partial (p u)}{\partial x} - \frac{\partial (p v)}{\partial y} - \frac{\partial (p w)}{\partial z} + S \tag{5}$$

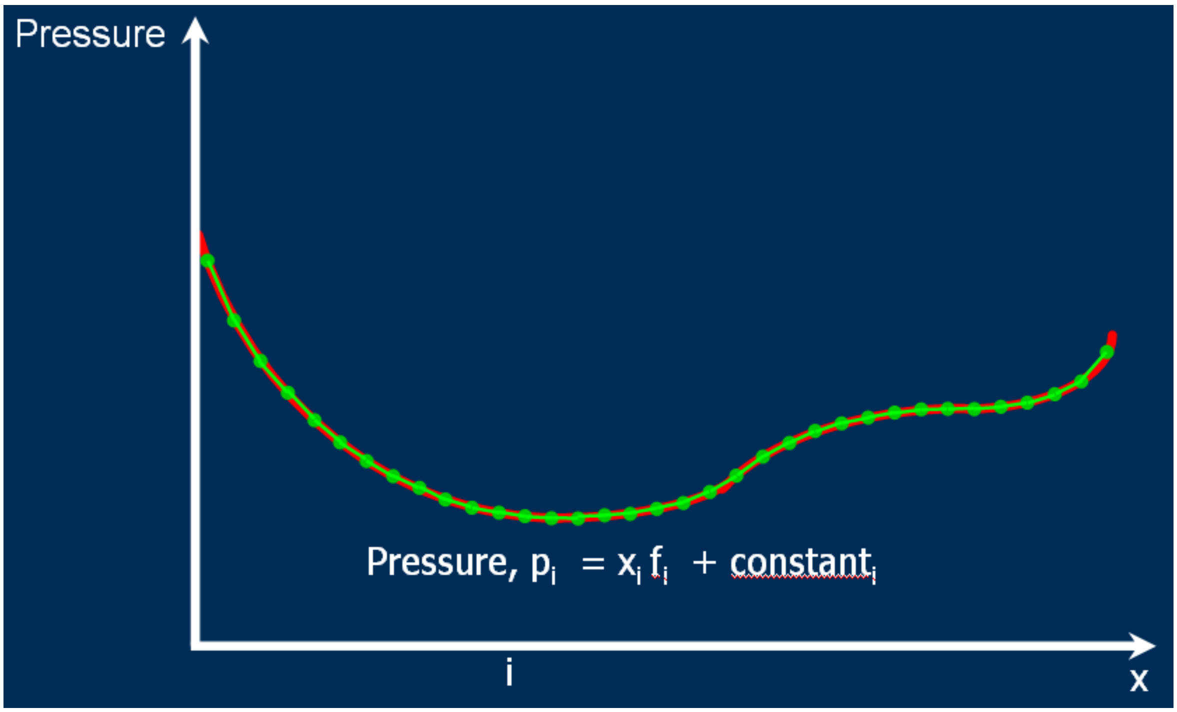
The Navier-Stokes Equations (the governing equations solved by AerOpt)

There is no hope of solving such a complex set of equations such as this by hand. In fact, even large supercomputers have to work hard to obtain solutions for 3 dimensional aerodynamic flows!

Inside **AerOpt** is a 2 dimensional CFD solver called *FLITE* which is designed to be efficient enough to run on a laptop or desktop PC with a Windows operating system. It will allow you to take shapes, test 'how aerodynamic' they are and it will then try to improve them for you – it does *aerodynamic optimisation.*

The development of CFD techniques has closely followed the development of the mathematical tools (or 'numerical methods') for solving partial differential equations. Numerical methods have been known since the time of Newton in the 1700s, but without the aid of the computer, the full exploitation of these techniques was impossible.

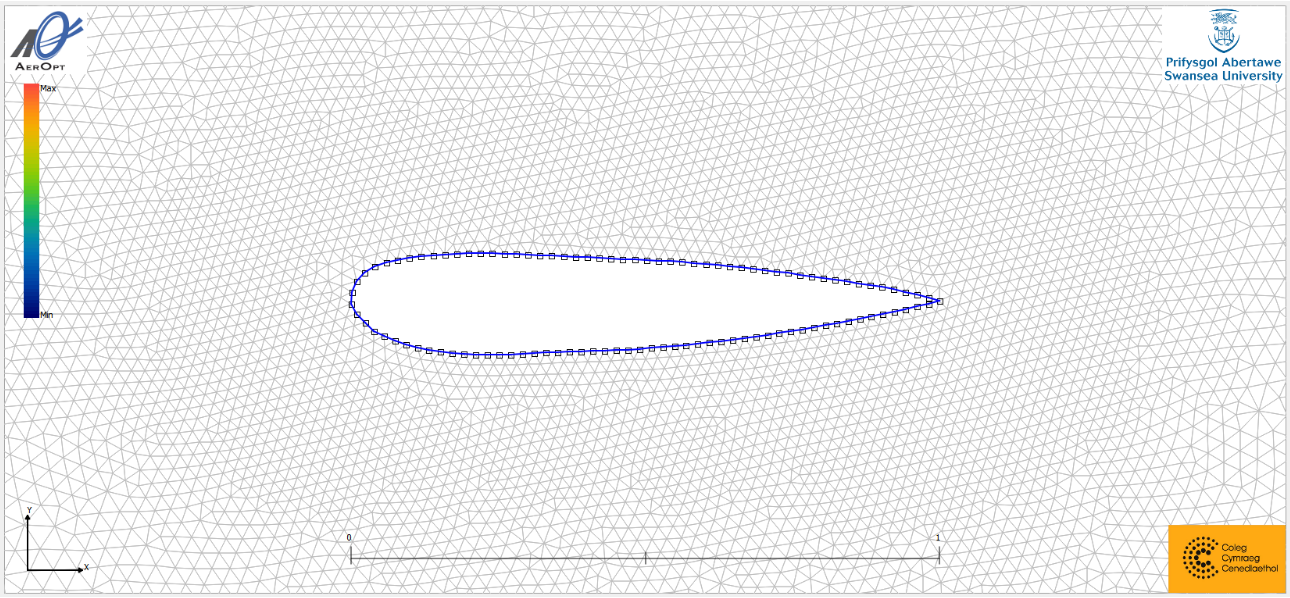
Modern CFD has its roots in the 1950s with the advent of the digital computer. At the heart of all CFD schemes is the fundamental question of how to represent a continuous function (e.g. a curve) in a digital form (e.g. by sampling). In other words, how should a computer store a function at an infinite number of points (i.e. every possible position in space and time) in some finite way, and as accurately as possible?



Example of the discretisation / approximation of a pressure function

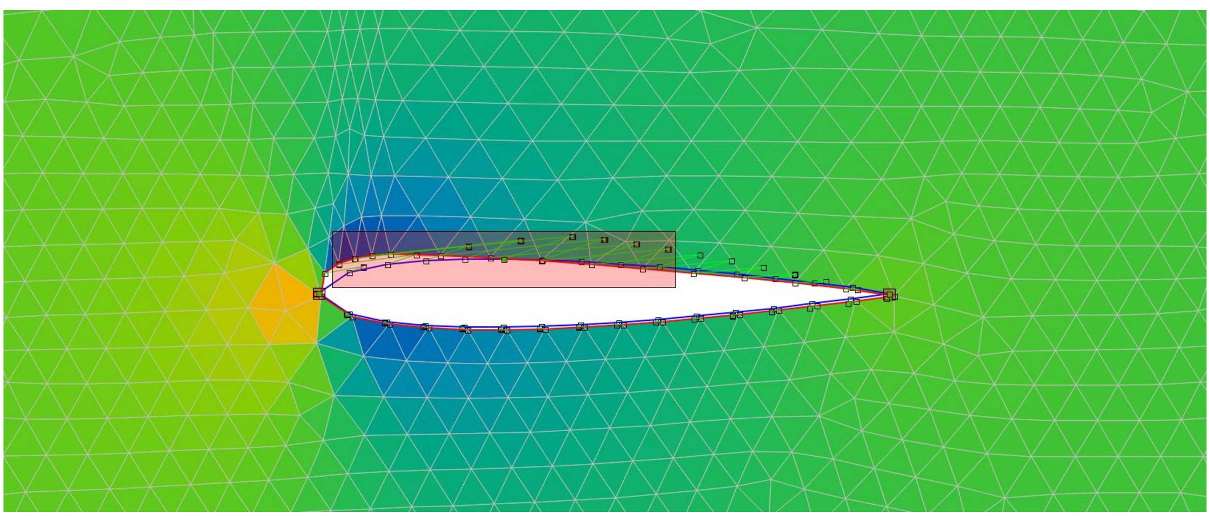
In the example above, a pressure function has been 'discretised' so that the value of the function at a finite number of 'nodes' is stored and a linear interpolation (straight line) of the solution is assumed between the nodes. The jump between each node is referred to as an element, and hence the solution method is often referred to as the *Finite Element Method*.

The most popular method of achieving a 2D finite element solution is to discretise the solution domain into a finite number of elements forming a *mesh* and to then apply a suitable algorithm (computer program) to values stored at the intersections of the mesh (the *nodes*) to solve the governing equations, in our case, the Navier-Stokes equations. The CFD solver in **AerOpt** uses a mesh of triangles as shown in the figure below:



2D Mesh of triangles surrounding an aerofoil created using AerOpt

Once the CFD solver has solved the Navier-Stokes equations it can then work out things that are of interest to the aerodynamicist such as the lift and drag coefficients of the shape being studied. It can also show how properties of the air, like pressure, vary around the object.



Pressure plot around an aerofoil in AerOpt (Red = high pressure, BLUE = low pressure)

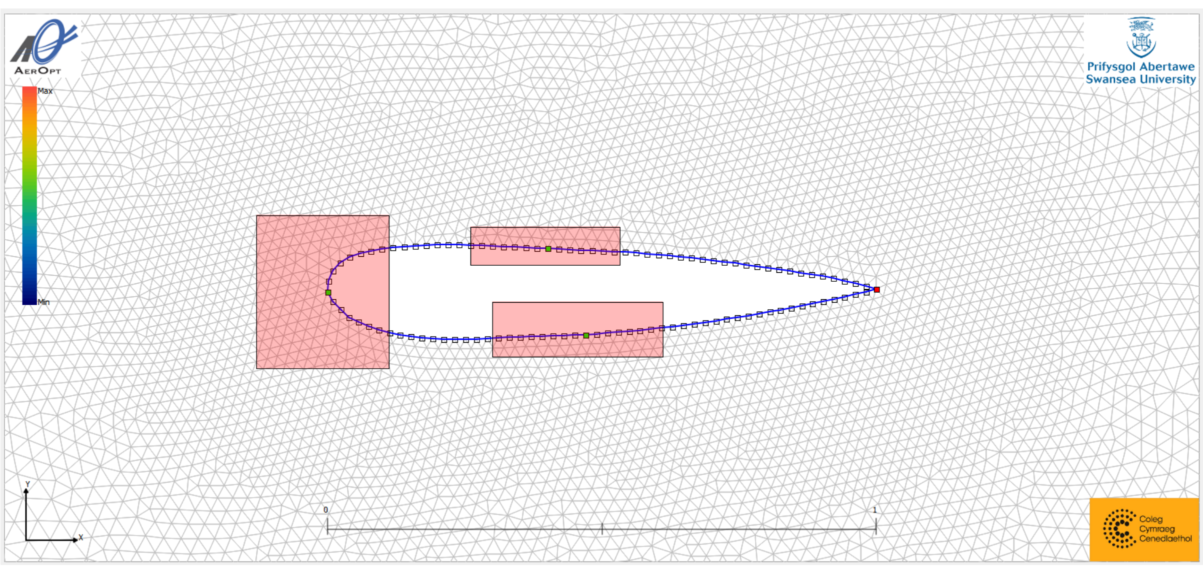
Optimisation of the Design

To start the process of optimisation, the designer needs to decide what it is he or she wants to improve. In **AerOpt** this is referred to as the *fitness* of the design. The fitness is how good the design is at achieving what the designer wants. For aerofoils the designer often wants to increase the Lift:Drag ratio. So the higher the Lift:Drag ratio, the higher the fitness of a particular design.

The **AerOpt** program uses an optimisation technique known as an *evolutionary algorithm*. Evolutionary algorithms use the basic principles of natural evolution (first proposed by Charles Darwin in his famous 'Origin of Species') to continuously improve a population over time using a form of 'inter-breeding' of designs. The specific algorithm used by **AerOpt** is called the *Modified Cuckoo Search* and was developed by researchers at Swansea University.

Control Nodes

The shape that you are modifying in **AerOpt** is defined using a set of nodes connected in a 'join-the-dots' style. Moving these nodes around changes the shape and this can either increase or decrease the fitness of the design. If all of the nodes were allowed to move independently from each other the number of options (or *degrees of freedom*) allowed would be massive and the optimiser would run very slowly. So, to avoid this problem, the user must select some of the nodes on the boundary as *control nodes*, set limits on how much each of these control nodes can move and then this will determine the positions of all the other boundary nodes defining the shape.



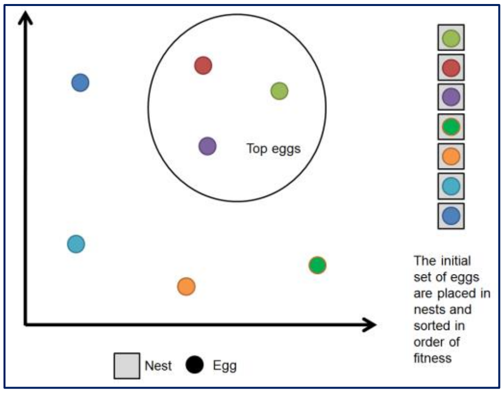
An aerofoil shape 'controlled' using 4 control nodes (note that the control node at the right tip is fixed in position)

Modified Cuckoo Search

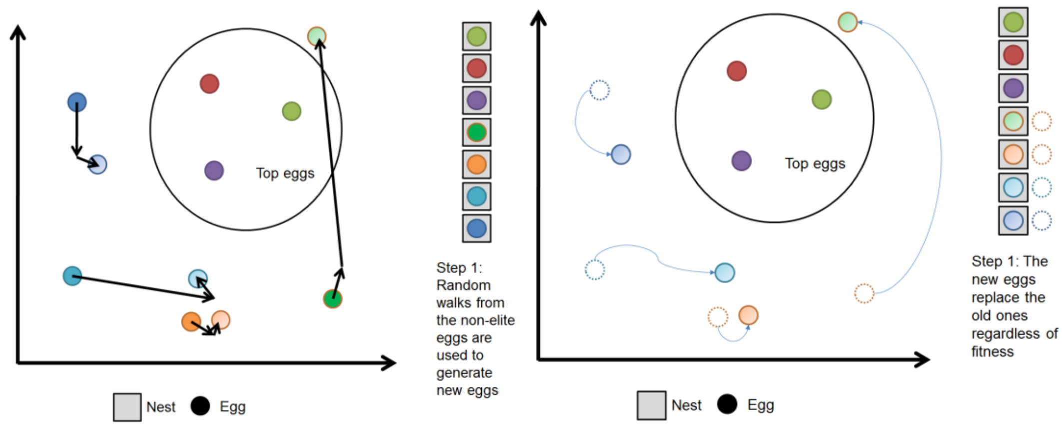
The Cuckoo bird in nature – it has just hatched in the nest of another species of bird

The goal of the Modified Cuckoo Search in **AerOpt** is to improve the fitness of the aerofoil design e.g. increase the lift:drag ratio or increase the downforce. The algorithm is inspired by the breeding behaviour of the Cuckoo bird in nature. Cuckoos, in the wild, do not build their own nests. Instead, they lay their eggs in nests of other birds and hope that the 'host bird' does not recognise that there is an 'alien egg' in their nest. The host bird, therefore, does the incubating on behalf of the Cuckoo (which is rather devious on the part of the Cuckoo). However, if the host bird recognises that the egg does not belong to itself then it will discard the Cuckoo egg, the egg is destroyed and the Cuckoo must try again with a new egg. You could think of the fitness of the Cuckoo's egg as how close it is to mimicking the host bird's egg. This aggressive removal of eggs that have low fitness is at the heart of the Modified Cuckoo Search algorithm. This is how it works:

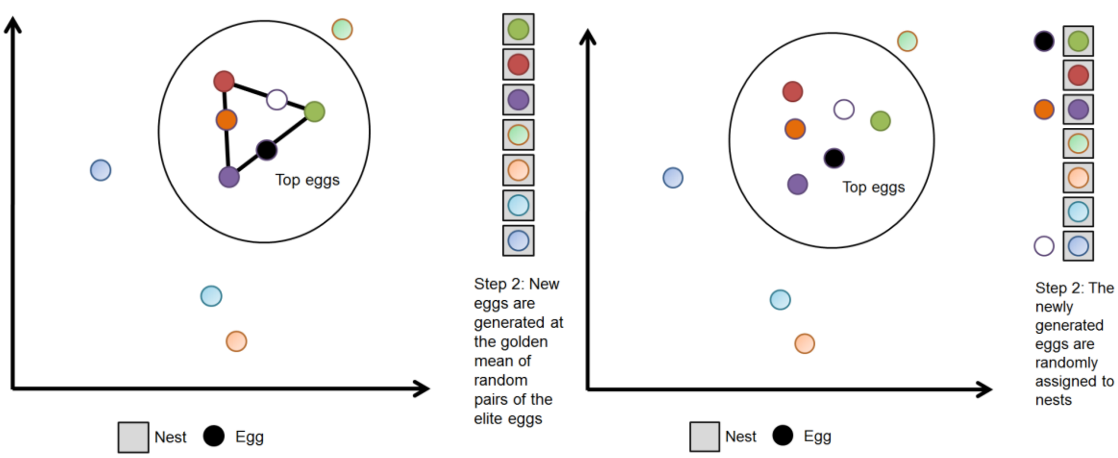
Each design (or aerofoil shape) that is tested corresponds to an egg and every egg lives in a nest. The designer needs to choose how many nests to use. In the diagrams below, think of the position of an egg within the axes as representing a particular design (in reality when using lots of control nodes to define the design it is more complicated than this). After an initial testing of a random selection of designs (which we will from now on refer to as eggs), they are sorted in order of fitness from best to worst and the best eggs are identified as 'top eggs' i.e. the eggs not discarded.

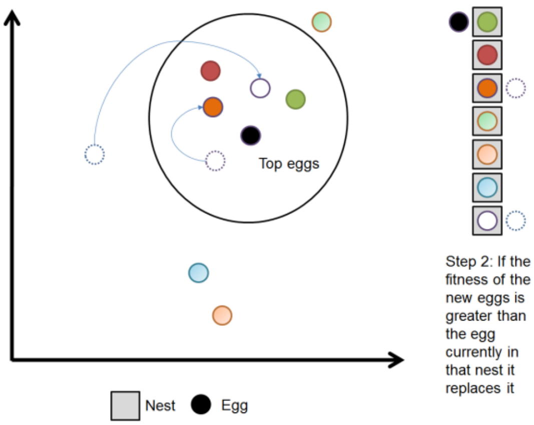


STEP 1: Any egg that is not a top egg is discarded, thrown out of its nest and replaced by a randomly generated new egg.

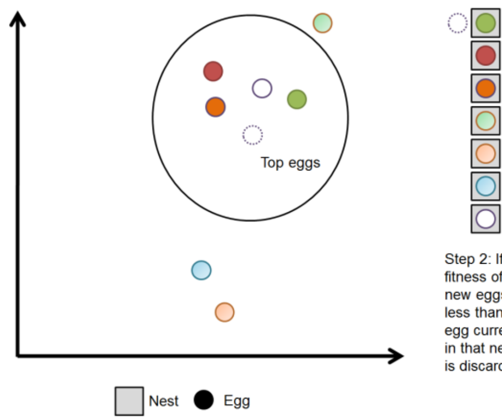


STEP 2: An 'inter-breeding' occurs between the top eggs in an attempt to combine the positive characteristics of these good designs. These new eggs are randomly assigned to a nest. If the egg is better than the egg already in the nest it replaces it and if not it gets discarded.



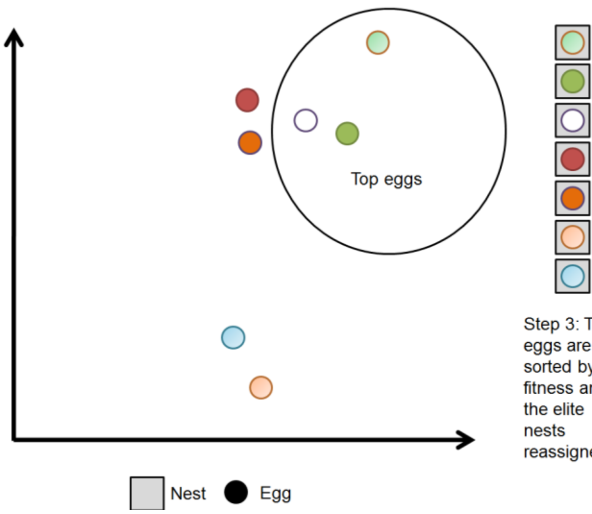


Step 2: If the fitness of the new eggs is greater than the egg currently in that nest it replaces it



Step 2: If the fitness of the new eggs is less than the egg currently in that nest it is discarded

STEP 3: The eggs are once again re-sorted in order of fitness, new top eggs are defined and the process repeats itself. Every cycle of this process is referred to as a *generation*.



Step 3: The eggs are sorted by fitness and the elite nests reassigned

It is important to note that the more nests (and therefore eggs) you select, the greater the chance of finding the best design but also the longer your computer will take to complete each generation.

All of this happens behind the scenes within **AerOpt**. What you get to see as the designer is the Graphical User Interface (GUI) and this is described in the next section: HOW TO RUN AerOpt.

3) How to run AerOpt

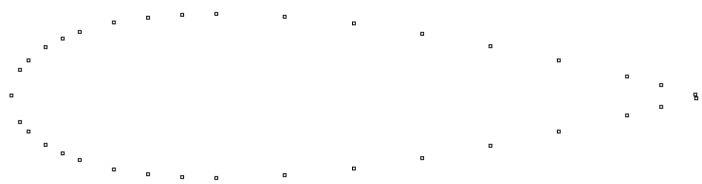
Open the AerOpt program by clicking on *AerOptGui.exe* in the **AerOpt** folder and you should see a screen that looks like this:

There are three sections to the screen: the *Settings Window*, the *Design Window* and the *Information Window*.

STEP 1 – Loading a starting shape/design

The starting point for your design should be a list of coordinates that define the points that form the outline of the shape. These can be ordered either clockwise or anti-clockwise. An example is shown below:

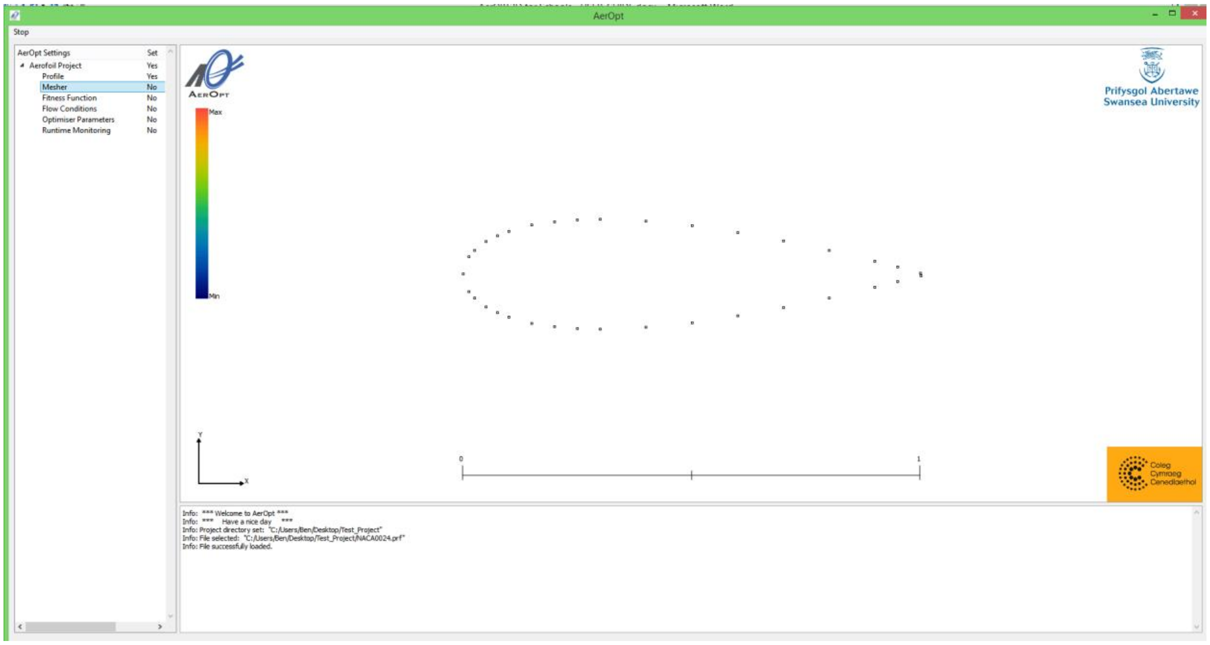
1.00000	0
0.95196	0.02240
0.90320	0.04099
0.80464	0.07447
0.70487	0.10312
0.60405	0.12674
0.50235	0.14474
0.40000	0.15606
0.29401	0.15738
0.24111	0.15287
0.18858	0.14416
0.13674	0.13045
0.08611	0.11012
0.06153	0.09651
0.03775	0.07942
0.01536	0.05624
0.00530	0.03964
0.00000	0.00000
0.01970	-0.03472
0.03464	-0.04656
0.06225	-0.06066
0.08847	-0.06931
0.11389	-0.07512
0.16326	-0.08169
0.18858	0.14416
0.21142	-0.08416
0.25889	-0.08411
0.30599	-0.08238
0.40000	-0.07606
0.49765	-0.06698
0.59595	-0.05562
0.69513	-0.04312
0.79536	-0.03003
0.89680	-0.01655
0.94804	-0.00964
1.00000	0.00000



Note that it doesn't matter what size the shape is. **AerOpt** will automatically scale the shape so that it sits from 0.0 to 1.0 in the x-axis. These coordinates should be stored in a plain text file with file extension .prf (standing for *profile*) and can be created in a simple text editor such as WordPad. Some example .prf files have been provided with the software to help get you started.

Right click on *Aerofoil Project* in the *Settings Window* and choose *Set Project Directory*. This will allow you to select a folder somewhere on your computer where all of the data generated by **AerOpt** will be saved. Note that you could create a new folder for each time you run **AerOpt** to help keep your results separated.

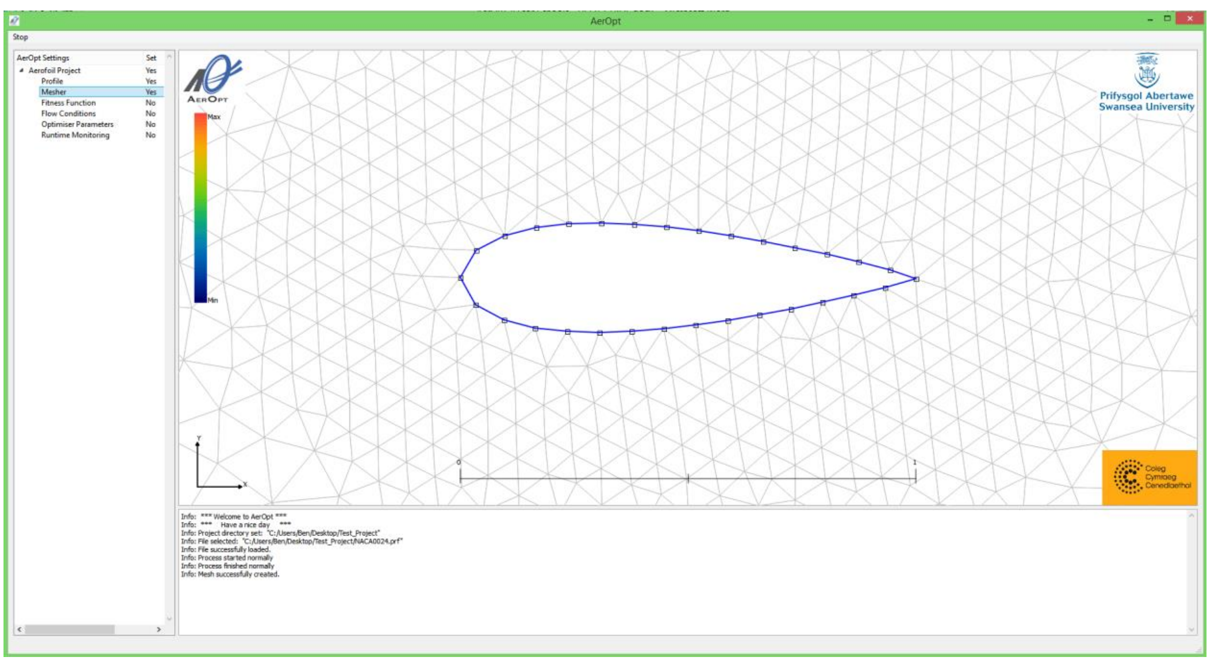
Right click on *Profile Data* and select *Import Profile*. From here you will need to select the .prf file containing the shape that will be the starting point for your design. Once completed the points defining the design will be shown in the *Design Window*.



STEP 2 – Generate a CFD mesh

Right click on *Mesher* and then *Run Mesher* and select the fineness of the mesh you want to create. You have three options: *Coarse*, *Medium* or *Fine*. Note that the finer (i.e. more elements) in the mesh, the more accurate the CFD solver will be but the longer it will take to run. There is a compromise to be made here that could be experimented with.

Click OK and the mesh will be generated and you should see something that looks like this:



STEP 3 – Select the fitness function

It is possible to optimise your design for a range of different fitness functions. Right click on *Fitness Function* and make the selection from:

Lift:drag ratio, max lift, min drag, max downforce, min absolute lift (i.e. 0 lift or downforce)

This tells the optimiser what you want to improve the design to achieve.

STEP 4 – Select the flow conditions

Right click on *Flow Conditions* and choose:

Temperature – this is the atmospheric temperature (in K), recommended to leave as default setting

Pressure – this is the atmospheric pressure (in Pa), recommended to leave as default setting

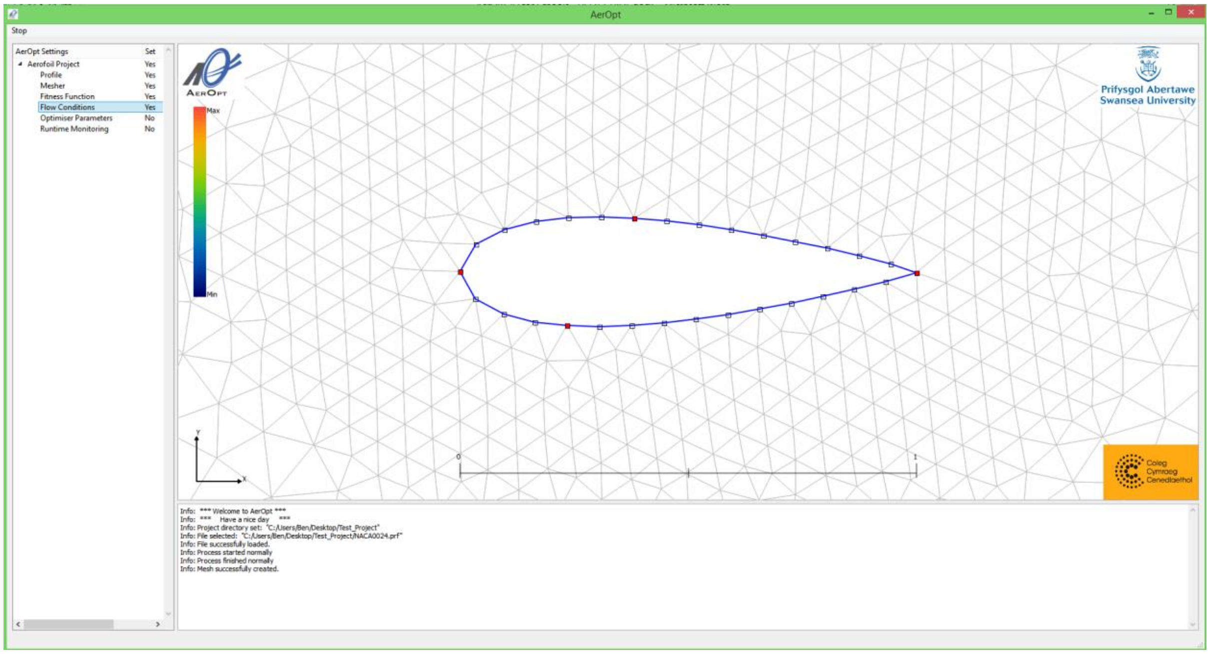
Mach number - speed of the flow relative to the speed of sound (< 1.0 = subsonic, > 1.0 = supersonic)

Angle of Attack – angle at which the oncoming flow hits the aerofoil

Reynolds number - in this version of the software it should always be left at 0

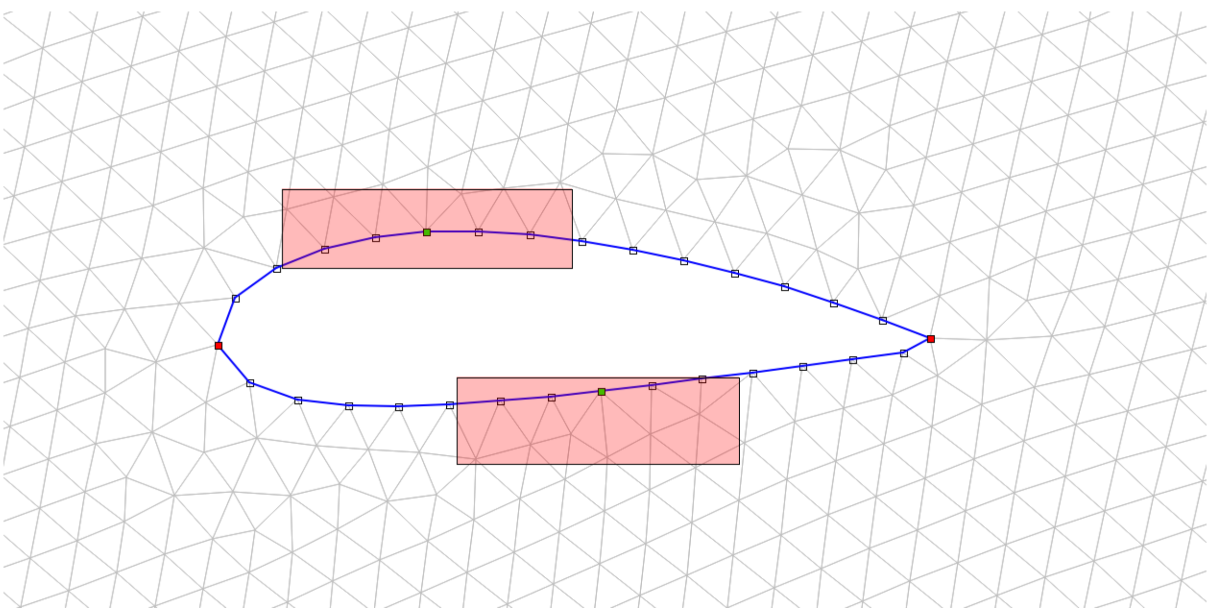
STEP 5 – Select and constrain control nodes

This is perhaps the most important part of the process where the role of the designer is crucial. You need to choose the nodes on the boundary that will become the *control nodes*. The movement of these control nodes will define the different designs that are possible. Double clicking on nodes on the boundary will convert them into control nodes and they will turn to red as in the Figure below. Place control nodes in positions on the shape that you think will be important in improving the design. Note that the more control nodes you choose to use, the more flexibility you give the design to change shape but also the slower the optimiser will run. Again, there is a compromise to be made by the designer here.



Now you need to decide how much you are going to allow each of the control nodes to move. You do this by right clicking each control nodes and adjusting the allowed x and y direction movements. Note that if you leave these values at zero then the control nodes will be pinned in place and will not move.

Once you click OK, red boxes will show the allowed movement of each of the control nodes.



STEP 6 – Set the optimiser parameters

Right click on *Optimiser Parameters* in the *Settings Window* and choose the optimiser parameters:

Number of nests – number of designs that are tested at each generation

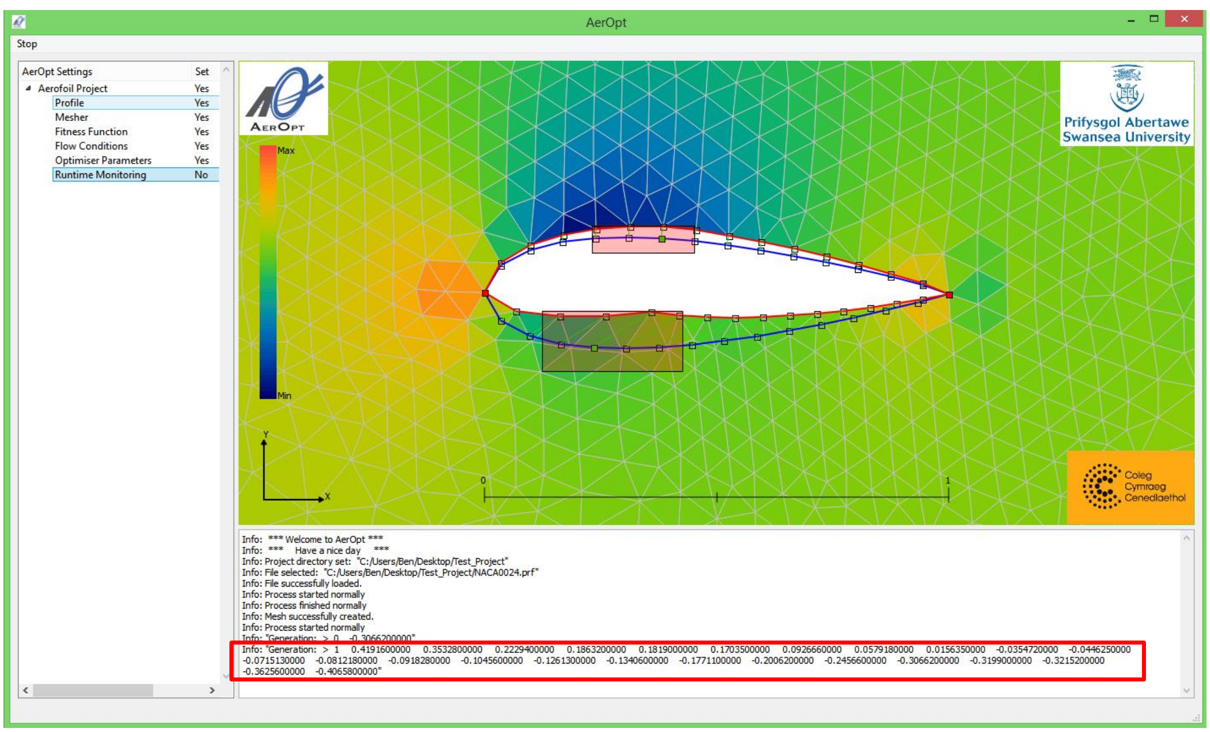
Number of generations – the number of 'design iterations'

Percentage of eggs discarded – percentage of eggs that thrown out to be replaced (the remainder are retained as 'top eggs' for inter-breeding

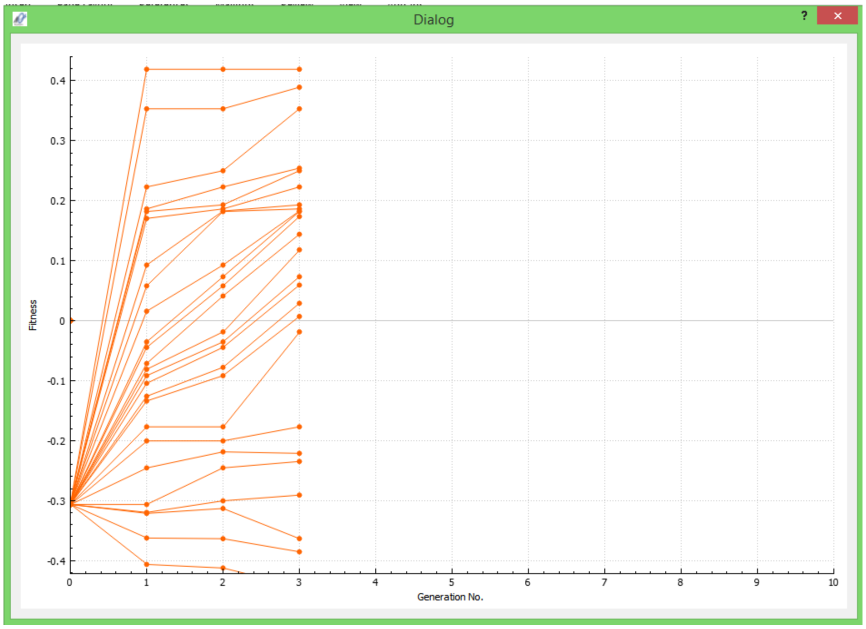
N.b. for more details on what each of these parameters means please see the theory section: **2) Theory – How does it work?**

STEP 7 – Run the optimiser and improve the design

Right click on *Runtime Monitoring* and select *Run AerOpt*. This will start the process of Modified Cuckoo Search generations using the CFD solver and over time you will see your design improve. The *Design Window* will always show you the best design in the current generation and how each of the nodes on the boundary have moved from the initial design. **AerOpt** will also plot a pressure plot around the shape to give you some idea of why the current design is an improvement on the previous design. In the *Information Window* you will also see a list of the fitness values of all of the designs tested at each generation



AerOpt also provides a graph that will update with each new generation showing the fitness of every design tested each generation. This also gives you a clear idea of how the best design design is improving.



AerOpt produces at output .prf file of the best design at each generation and this is saved in the *Output_Data* folder that will be created inside the *Project Directory* selected at the start of the run. This is really useful because you can use one of these .prf files to restart AerOpt (perhaps using different optimiser settings and control node positions) for continued improvement of the design.

If at any point you want to stop **AerOpt,** you can just click the *Stop* button in the top left corner of the **AerOpt** screen.

4) Common Problems and Frequently Asked Questions

- **Why does AerOpt run more quickly the higher the Mach number?**

The most expensive aspect of running AerOpt for the computer is the CFD solver that is embedded within it. The algorithm inside the FLITE CFD solver in AerOpt was designed to work most efficiently at higher speeds. This means that it can obtain solutions to the Navier-Stokes equations more quickly at higher Mach number and, in turn, the optimiser runs more quickly at higher Mach numbers.

- **What are the Navier-Stokes Equations?**

The Navier-Stokes equations are the governing equations of compressible fluid dynamics i.e. fluid flows (including air) in which the density of the fluid can change. They were derived by two scientists (Navier and Stokes) over two centuries ago and even though they are, mathematically, very complicated, they are based on three very simple principles: *conservation of mass*, *conservation of momentum* and *conservation of energy*.

- **Why does AerOpt sometimes stop working?**

AerOpt is not a commercial software package with lots of financial investment. It has come out of academic research at Swansea University and therefore a lot of work is still going on to full understand its limitations (you can help us with this!). This means that there might be occasions, and certain settings under which it stops working. For example, if you push the Mach number request to high, or ask the control nodes to move too far the algorithm that is running in the background might not be able to cope. Usually if this happens you will see an error message in the *Information Window* informing you that something has gone wrong. If there is no error message in the Information Window, it might just be that the CFD is taking a long time to run on your computer (perhaps because the mesh is too fine). You can check to see if the computer is actually still running by looking at what the processor is doing using your computer's *task manager*.

- **Some commonly used terminology:**

Mesh	This is the set of triangular *elements* on which a CFD simulation runs
Node	The nodes are the intersections of the *mesh* (and points on the shape boundary)
Element	An element is a triangular shape (defined by three nodes) within the *mesh*
Optimisation	This is the automated process of improving a design within the computer
CFD	Computational Fluid Dynamics – the method used by the computer to get aerodynamic flow solutions
Algorithm	An algorithm is simply a set of instructions carried out by the computer
Aerofoil	The name of a design that is the shape of a wing cross-section
fitness	The measurement of how good a design is
Evolutionary algorithm	A particular type of optimisation algorithm that is inspired by natural selection
Control nodes	The nodes on the shape boundary used by the designer to control the shape
eggs	An egg can be thought of as an individual design being tested by the optimiser
nests	These are the 'locations' where the eggs are held
generation	One cycle of the Modified Cuckoo Search algorithm

5) Examples and ideas for use in schools

Using the .prf files provided

To be completed…

Experimenting with different mesh fineness settings

To be completed…

Experimenting with different optimiser parameters

To be completed…

Competitions

To be completed…

Use in Practical Design Workshops

To be completed…

6) References

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S. Walton, O. Hassan, K. Morgan, M.R. Brown, *Modified cuckoo search: A new gradient free optimisation algorithm*, Chaos, Solitons & Fractals*, 2011*

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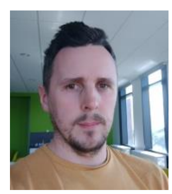
AerOpt was developed by the following researchers at Swansea University's College of Engineering:



Dr Ben Evans Mr David Naumann Dr Sean Walton Dr Matt Edmunds

If you have any questions about AerOpt or find out more about the ongoing research related to aerodynamic optimisation at Swansea University, please contact Dr Ben Evans at **b.j.evans@swansea.ac.uk**

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