Adaptive Flapping Wings for Wind Tunnel Tests

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Within the scope of a corporate project of Honda Research Institute Europe, the Darmstadt University of Technology, and the Fraunhofer Institute for Structural Durability and System Reliability (LBF) Flapping Wings are developed. The complete twisting during one flap cycle of this wing and the adjustment of the rear flaps are optimized by an algorithm based on evolution strategies. The wing is divided into four segments, which are uniformly distributed over the longitudinal direction of the wing. After that, the functional capability of the adaptive system is verified in a wind tunnel of the Darmstadt University of Technology.

The idea of this project is a deeper analysis of the aero dynamical principle of the bird flight. The following article describes in detail the difficulties of integrating suitable actuators and sensors into the small installation space, without exceeding the costs, but with enough dynamics and strength to twist the wing consisting of glass reinforced plastics (GRP). Thereby, the stiffness of the whole construction should not fall below a point where the adjusted shape of the profile disappears because of the aerodynamic load in the stationary case.

A 4-digit symmetric profile based on the National Advisory Committee for Aeronautics (NACA) with a thickness ratio of 12% was used for the wing. The twisting of the wing is to be accomplished first with a tension-torsion coupling. If the direction of the glass fiber in the GRP is chosen in the right way, the wing twists when it is lengthened. Therefore, several finite element (FE) calculations are performed, which prove the theoretical feasibility. But requirements prevent this procedure. Instead of the tension-torsion coupling by means of directing the glass fiber, a mechanical system with flexure hinges driven by Fluidic Muscles™ is used. The rear flap adjustment is accomplished with pneumatic round cylinders. The torsion angle and deviation of the rear flaps are acquired for every wing segment by strain gage beam arrangements. With these arrangements it is possible to use an easy adjustment control to trigger the valves of the Fluidic Muscles™ and the pneumatic round cylinders at the trailing edge.

The graph of the nominal values by one flap of the wing for triggering the actuators is generated by an optimization algorithm based on evolution strategies. There are three variants fitting the strategy parameters: The Global Step Adaptation (GSA), the Individual Step Adaptation (ISA), and the Covariance Matrix Adaptation (CMA). All variants are empirically evaluated regarding their behavior due to perturbations and the coupling of parameters. The two most promising strategies, the GSA and CMA, are used in the wind tunnel tests. The tests are performed with an air speed of approximately 64 km/h and a flapping frequency of 0.5 Hz. After the optimization an improvement of the so called fitness of the factor of 3 is achieved in spite of high signal noise.

The wind tunnel tests are showing that it is possible to significantly improve the air stream properties of an adaptive wing with a suitable optimization strategy in spite of limited dynamics and with a small range of variation.

Motivation

The detailed fluid mechanical phenomena of flapping wings are not fully understood to date. Complex shapes, shape variations and their control which emerged during the evolution of birds enable efficient flight under variable conditions.

In this work, we make a very first step into the direction of simulating and understanding these complex processes. Here we follow an analysis through synthesis approach, i.e., we build a system with similar degrees of freedom as a natural wing and optimize the dynamic shape control during a flapping period using evolutionary algorithms.

The wing geometry has to be adaptive in order to enable online (in the windtunnel) variations. We will describe the adaptronics of the wing model in the next sections and demonstrate the effectiveness of our approach.

Furthermore, we will show that evolutionary algorithms can be successfully applied to the control of dynamic shape variations during flight especially under the constraint, that the evolution modifies the wing model directly in the windtunnel without manual interaction. This closed loop optimization involving variations and measurement is necessary to make the whole process feasible. At the same time, it requires a reliable adaptronic design and measurement of the fluid dynamic properties that are subject to optimization.

Figure 1: Gray goose by Marc Weis ©

The adaptive wing model has to be able to twist the wing profile and the flaps have to be able to move. To make the model more variable, we divided the wing into four separately operable segments. Also the wing has to be waving like a birds wing (Figure 1). Therefore, the trajectory over one flapping period of the following parameters was subject to optimization:

- the frequency of the wave
- the degree of the twist for four segments
- the rotational degree of the four segments flap

In total, the time course of nine parameters has to be optimized for one cycle.

First Design Attempt

The first idea to accomplish the twist of the wing was to use the tension-torsion coupling of the wings skin. The wings skin consists of GRP, and if the direction of the angle of the fiber is chosen in the right way it is possible to twist the wing by a strain in the longitudinal direction. The degree of twist is also dependent on the stiffness of the fiber composite and the force that will be needed to deform the wing. To get some information about the dependencies we create an FE model of the skin. The direction of the fiber, the thickness of the composite, and the amount of strain serve as input. The results of the simulation are the angle of the twisting and the force that will be needed to deform the wing.

The profile of the wing is a so-called 4-digit NACA 0012 profile (Figure 2). The first digit represents the relative camber. The second digit represents the camber position. The third and fourth digits represent the thickness (see e.g., Truckenbrodt, Schlichting [1]). The NACA 0012 is a symmetric profile and the thickness of 12% is chosen because of its stable behavior even at large angles of incidence.

The results of the simulation show, that it is theoretically possible to twist the wing by tension-torsion coupling up to an angle of about 2 degrees.

Figure 2: Coordinate system of the wing geometry

But the forces required to deform the wing are much too large for piezo ceramic actuators, which create a large force, but only a small strain. The fiber composite must be very stiff to produce the required twist angle, even if this means that the force required to deform the wing gets much too large. Therefore bigger actuators would be needed, but this is against the demand of small costs of the actuator system. The idea of using hydraulic systems was ruled out, because of the weight and the absence of hydraulic supply systems at the wind tunnel.

New Design and Initial Operation

Fluidic Muscle Actuator

To solve the problem an actuator can produce much more strain and has nevertheless enough power to twist the wing. One possible actuator is a so called Fluidic Muscle™ made by FESTO. It works with pressurized air and is able to generate a force of about 1500 N. The strain that can be generated with this force, is about 1% of its length. Unfortunately, it can generate only tensile loads. Therefore a mechanical gear is required to transform the tensile force into a rotational force without too much loss in performance. This can be accomplished with flexure hinges, which is described later on. First it was checked if the generated force is able to twist the wing. This is done by an FEM simulation. In the simulation the force is split into two equal parts. One part of the force is applied at the top of the thickest part of the profile. The direction of this force is in negative x-direction (compare to Figure 2). The second part is applied at the bottom of the thickest part of the profile. The direction of this force is in positive x-direction. The simulation result for one segment can be seen in Figure 3. The results indicate that it is possible to twist the wing with a fluidic muscle.

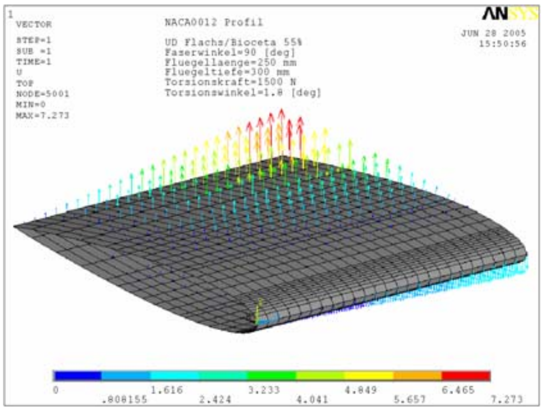

Figure 3: Displacement of the wing profile when a torsion force of 1500 N is applied

Proportional-pressure regulators (VPPE made by FESTO) are used to drive the muscles.

Later on it is exposed that the proportional-pressure regulators are to slow to exhaust the air. Therefore the dynamic of the twisting is not as fast as predicted and the flapping frequency must be reduced to 0.5 Hz. The only problem is to change the force direction of the fluidic muscle.

Flexure Hinges

As mentioned before, a tensile force must be transformed into a rotational force. This could be done with a screw-thread, but there will be much friction that costs even too much performance of the Fluidic Muscle™.

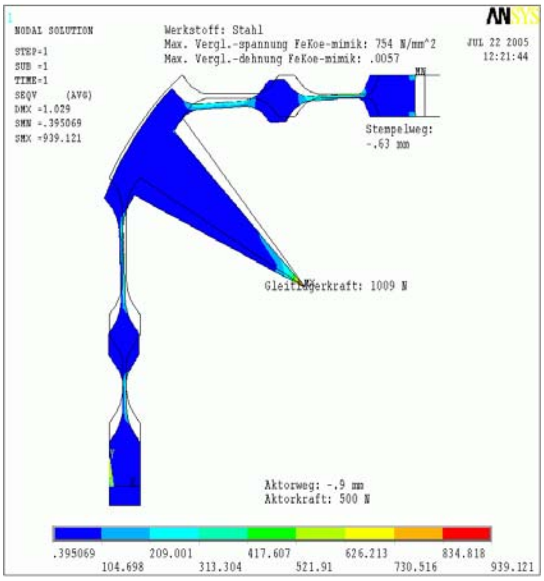

Figure 4: Displacement and stress of the first flexure hinge

Another way is to use flexure hinges. Flexure hinges are working without friction and without play. So any movement is performed directly to the wing and there is no loss. It is also possible to convert a linear movement into a rotation.

To design flexure hinges and to make the correct assumptions some experience of flexure hinges and several FEM simulations are needed. Several geometric parameters influence the performance of the flexure hinge, which depends on the movement of the driving section and of the driven section of the hinge. Finally it is dependent on a possible magnification of the movement.

First the linear movement of the fluidic muscle is transferred from the x-axis to the y-axis with one flexure hinge arrangement. The displacement and the stress can be seen in Figure 4.

Another hinge attached to the first one is transferring the linear movement from the y-axis to a rotation around the x-axis. The displacement and stress can be seen in Figure 5.

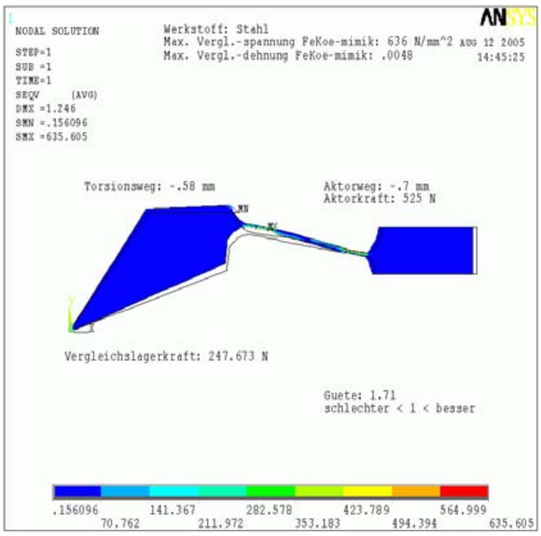

Figure 5: Displacement and stress of the second flexure hinge

The stress is tolerable in both cases if the right material is chosen. The used material is spring steel 50CrV4. The design of the complete flexure hinge arrangement can be seen in Figure 6.

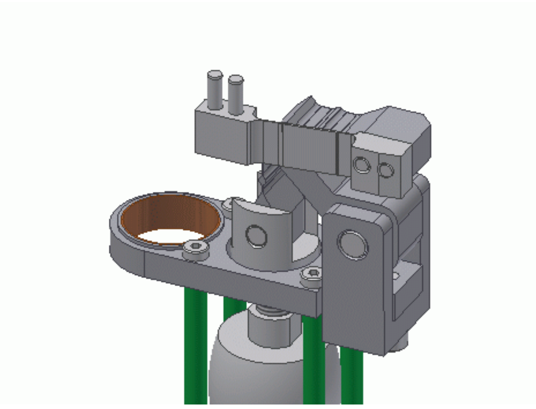

Figure 6: Complete flexure hinge arrangement

At the bottom of Figure 6 there can be seen the top of the Fluidic Muscle ™, which pulling down the first flexure hinge arrangement. This hinge is turnable embedded on the right hand side and so the upper right corner of the first hinge arrangement is turning left. To guarantee a linear motion of the two ends of the hinge arrangement without exceeding the stress limits the top-down-hinge and the left-right-hinge both consist of two hinges. So the bending stress could be better relieved. Also the second hinge consists of two hinges with a small lever between them. The right section is moved to the left by the first hinge arrangement. The upper left side of the hinge is fixed at the fin with the two pins and the fin is turnable embedded at the spar (compare to Figure 9). The fin is turned around the bar and the skin of the wing is twisted. Every module is fixed at the previous fin and the first module is twisting the whole segments two to four. The second module is twisting the whole segments three to four and the third module is twisting the whole segment four (compare Figure 7).

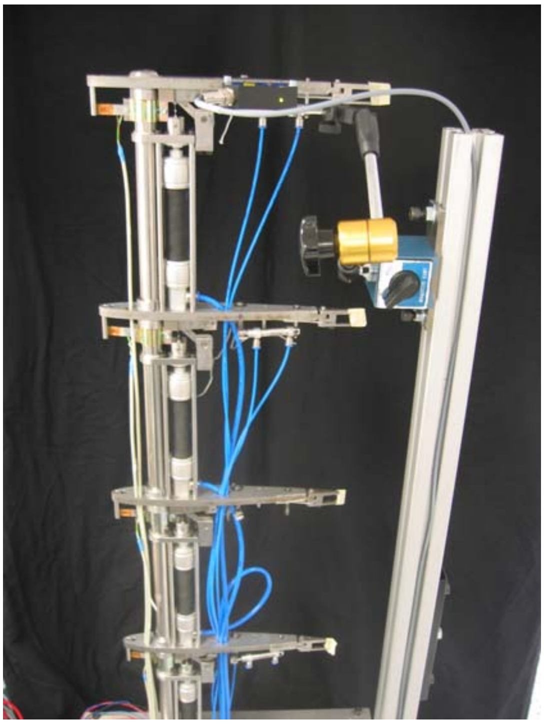

Figure 7: Complete wing interior at test rig

Flap Movement

For the positioning of the rear flaps, pneumatic round cylinders (type DSEU by FESTO) are used. Leverages and Bowden wires are used in order to convert the longitudinal movement of the cylinders into an angular motion of the flap. The positioning of the actuators is controlled by proportional directional control valves (MPYE by FESTO).

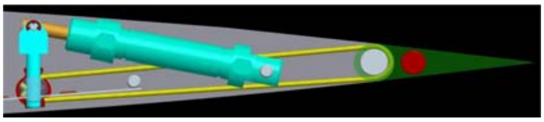

Figure 8: Design of the rear flap mechanism

Sensors and Measurement

The positions of the rear flap and the twisting of the profile of the four segments are measured by resistance strain gages bonded to bending bars (Figure 9). Since only small twisting and rotational angles have to be considered (max. 2° twisting per segment of the profile and about ±3° maximum rotation of the leverage for the positioning of the rear flap) the measured strain at the surface of the bending bars can be considered as nearly proportional to the angular position. The signals of the strain gages are amplified with an MAS MICRO II ™ of SWIFT GmbH to prepare the signals for use in the closed loop control system.

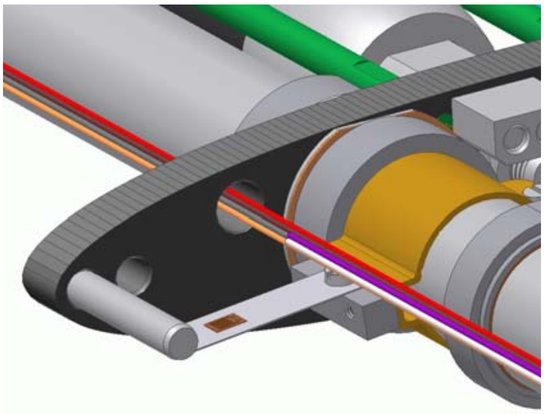

Figure 9: Strain gage bonded to bending bar to measure the twisting

Control and Implementation at the Wind Tunnel

During the flapping of the wing the target positions of the actuators are permanently altered in order to achieve optimal performance. The positions are determined by optimization algorithms on the basis of evolutionary strategies which are included into a Simulink model. Inside the wind tunnel the wing is fixed on a mounting which emerges from an opening in the bottom of the measuring section (Figure 10). The mounting itself is attached to a six component balance situated underneath the wind tunnel. Thus the wing is decoupled from the measuring section and stands free on the balance. The data collected by the balance is computed and the aerodynamic forces (ascending, resisting, lateral force) and moments (pitching, yawing and rolling moment) are derived. Depending on the optimization problem, the relevance of the loads can vary. E.g. for minimizing the ascending force of the wing, the fitness of the individuals of the evolutionary algorithm only depends on the measured data of the ascending force.

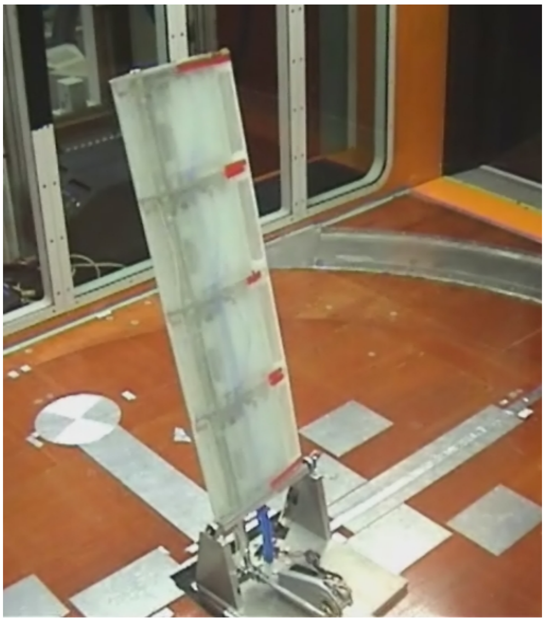

Figure 10: Adaptive Flapping Wing in Wind Tunnel

In order to generate the analog signals for control of the proportional valves and regulators and for streaming purposes of the sensor signals, a digital signal processing system (DSP-system) by dSPACE is used. With dSPACE and the associated interface software ControlDesk, the experiment can be coordinated completely from the PC. For adjusting the set point values, a simple displacement feedback-controller is programmed in Simulink and downloaded onto the processor module of the dSPACE system. All internal conditions of the controller can thus be observed and changed within the ControlDesk GUI.

The angular position control of the twisting of the wing and the rear flaps is realized by a digital PID-controller, which is included in the dSPACE environment.

Simulink-dSPACE Interaction

As previously mentioned the optimized positions for twisting the profile and angular positioning of the rear flaps are calculated by use of evolutionary control strategies which are implemented into a Simulink model. The set point values are then transmitted to dSPACE and the actuator positions are adjusted by the PID-controller, which runs on the processor board of the dSPACE system and is executed in the background. The data exchange between the evolutionary algorithm Simulink-model and the dSPACE regulation is coordinated via a Matlab program. The angular setpoint values which are calculated by the Simulink-model are sent to the dSPACE system. Vice versa sensor data is collected for visualization purposes. In the following, the Simulink-Matlab-dSPACE interaction and the various functions of each module will be briefly explained.

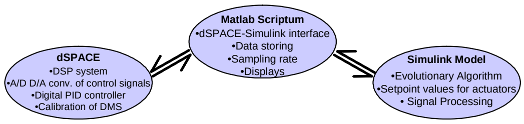

Figure 11:Simulink-dSPACE interaction

As illustrated in Figure 11 the Matlab program has to fulfil several tasks. Firstly it coordinates the data exchange between the Simulink model, where the set point values are calculated and the dSPACE system, where the analog control signals for driving the actuators are generated. Within one time step the actual sensor data provided by the strain gages are read. With this information new twisting and rotational angles are calculated and sent to the dSPACE system. Secondly the temporal succession of the data exchange is defined by the interface program by means of a Matlab timer object. Furthermore a graphical user interface (GUI) facilitates the use of the program. So the experiment can easily be started and suspended and some selected measured values can be observed in real time in diagrams, which are included in the GUI (Figure 12).

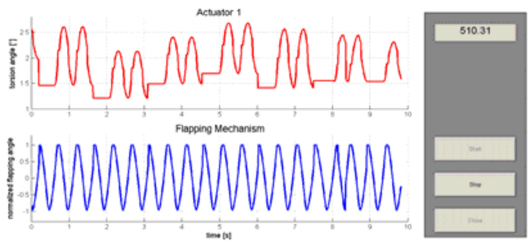

Figure 12: Matlab GUI for experiment control; above: torsion of the first segment of the wing profile; below: angular position of the flapping mechanism

The calculation of the set point values takes place inside the Simulink model. The new positions are derived by evolutionary optimization strategies. The acquired data is delivered by the six component balance, whereon the wing is attached. The aim is the minimization of a cost function which is previously determined out of the goals of control (e.g. minimum ascendancy).

With the dSPACE DSP system the predetermined actuator positions are adjusted and sensor data is processed. For the minimization of the control deviation and rapid approach to the set point values the parameters of the digital PID controller have been tuned. Furthermore the strain gages must be calibrated before the experiment. These tasks are handled by the GUI which is programmed with the associated ControlDesk software.

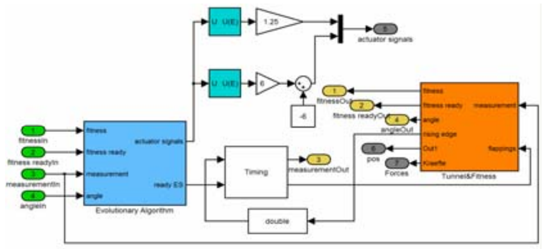

Figure 13: Simulink model: set point value calculation applying evolutionary strategies

The data transfer between the Simulink model and dSPACE takes place with a sampling rate of 100 Hz, which is previously defined by a Matlab timer object. The model is permanently held in compiled state after the experiment is started and is “pushed further” with every time step from the Matlab program. With this method the Simulink model is executed in real time, making it applicable to the experiment control purpose. The drawback of this procedure is that all inner states of the optimization method have to be stored, because feedback loops are not applicable. Due to the problem that the local variables of the model are cleared after every time step, feedback paths lead to inconsistencies. Therefore the feedback parameters have to be read out at one time step and handed back at the next time step (see fig. 13 Simulink model: yellow outputs and green inputs: fitness, fitness ready, measurement, and angle).

Digital PID

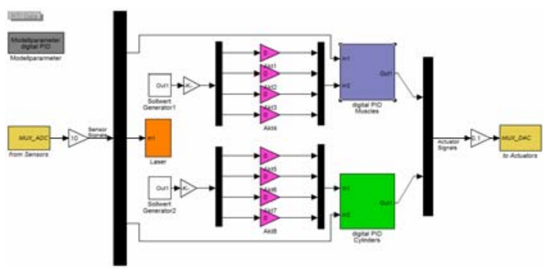

Figure 14: Simulink block diagram containing digital PID controllers for download to the dSPACE processor module

In Figure 14 the model containing the data connections to the optimization routine and the digital controller for actuator positioning is presented. This model is programmed with Simulink and must be downloaded on the processor module of the dSPACE DSP-system, which is executed in the background. The yellow coloured blocks symbolize the digital to analog conversion of the actuator signals (to actuators) and the analog to digital transformation of the sensor signals (from sensors). The set point values from the optimization Simulink model are passed to the magenta coloured gain blocks, where the labels Akt1 to Akt4 represent the four Fluidic Muscles^{TM} of the four wing segments and Akt5 to Akt8 stand for the pneumatic cylinders. The blocks labelled "digital PID" contain the PID controllers for the fluidic muscles (blue) and for the cylinders (green). The orange "Laser" block is included for calibration purposes of the strain gage sensors using a laser proximity sensor. Figure 15 shows the GUI for accessing the control and calibration parameter.

Figure 15: ControlDesk GUI (dSPACE interface)

Optimization

Evolutionary Algorithms

Principles

Evolutionary Algorithms are direct pseudo-stochastic search methods which mimic the principles of Neo-Darwinian evolution, see e.g. by Fogel [2]. A population of possible solutions described e.g. by a vector of continuous parameters, the objective variables, is adapted to solve a given problem (e.g. minimisation / maximisation of forces over several generations. The adaptation occurs by variation of solutions contained in a population and by selection of the best solutions for the next generation. The variations can be classified as purely stochastic (usually called mutation) and combinatoric / stochastic (usually called recombination or in the context of genetic algorithms crossover). Schematically the evolution cycle is shown in Figure 16.

The coding and decoding processes have been explicitly included. They describe the transition from the genotype, which is also called the representation or the blueprint, to the phenotype, which is evaluated. The representation is one of the most important factors in the design of evolutionary algorithms. Together with the search operators most of the current algorithms can be classified with respect of the representation they use, e.g. genetic algorithms, evolution strategies, genetic programming and evolutionary programming.

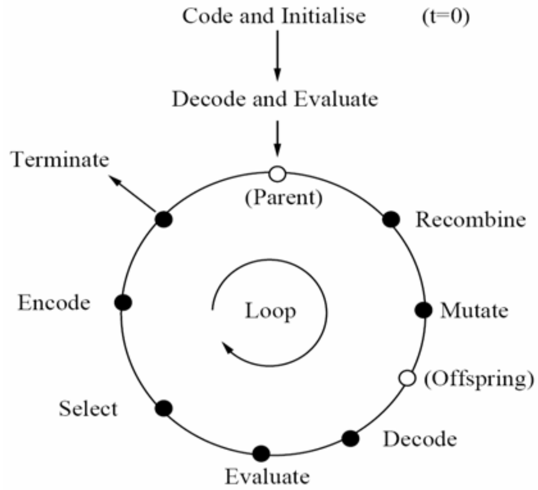

Figure 16: The evolution cycle

Evolution strategy

In the experiments described in this paper Evolutionary Strategies (ES) are applied. In this algorithm the essential variations during the evolutionary search are mutations which are realized by adding normal distributed random numbers to the objective variables. They determine the distribution of the offspring around the parent. The variances σ^2 of the normal distribution are called the strategy parameters of the search process and their values determine the width of the search. The variances have to adapt during the process to the local topology of the search space. This process of self-adaptation is one of the key principles of ES. It relies on a "second-order" or indirect selection of the strategy parameters which are part of each individual.

In the standard evolution strategy only a diagonal covariance matrix is used, i.e. the mutation of the objective variables $\vec{x}$ is carried out by adding $N(0, \sigma_i^2)$ distributed random numbers z_i to each component x_i. The "step sizes" σ_i are also subject to mutations (log-normal distributed) both for each component separately (parameterized by τ) and overall (parameterized by τ').

Thus, the individual consists of both the objective and the step-size vector. Formally, the standard evolution strategy with self-adaptation can be expressed as follows: (see e.g. Schwefel [3])

$$\begin{aligned} \sigma_i(t) &= \sigma_i(t-1)\exp(\tau' z)\ \exp(\tau z_i) \\ \vec{x}(t) &= \vec{x}(t-1) + \vec{z} \\ z_i, z &\sim N(0,1),\ \vec{z} \sim N(\vec{0}, \vec{\sigma}(t)^2). \end{aligned}$$

The selection in ES is typically deterministic, i.e. from μ parent individuals, λ offsprings are produced and from these the best μ individuals are selected to form the parent population of the next generation. This method is usually abbreviated to (μ, λ)-selection.

Representation

The four actuators responsible for the torsion of the wing and the four responsible for the position of the trailing edge flap determine the geometry of the wing at a given time t. The target of the optimization is to find the optimal actuator trajectory $a_i(t)$ of the 8 actuators A_i, i = 1 . . . 8 for the time t during one period T of the flapping movement. In case of a static wing model in which the geometry of the wing is fixed during the measurement it would be sufficient to encode eight parameter of the model for each individual. Here the target is the optimal time dependent setting of the actuator values during the whole period of the wing movement. Therefore the optimization of the geometry is equivalent to the optimization of a functional defining the actuator trajectory over time. A proper choice of an encoding for the functional describing the actuator signals is necessary and crucial for the optimization. In the described system the actuator signals for the i-th actuator are represented by a spline curve which is determined by a set of control points C_i. The necessary knot points of the spline are constant during the optimization and chosen equidistant. In this way the dimensionality of the search space is decoupled from the sampling frequency of the actuator values. Due to the fact that the velocity of the wing angle is not regulated and undergoing small changes during the measurement due to changing aerodynamic forces the actuator values are encoded as a function of the wing angle α instead of the time t. In this way it is guaranteed that the actuator setting is synchronized with the flapping movement even if the frequency of the wing movement is changed. The actuator settings are given as the value of the spline function $a_i(\alpha) = s_i(\alpha, C_i)$. In this way the actuator settings are represented as a function of the actual wing angle. Because of the periodicity of the flapping movement of the wing the geometry change and therefore the setting of the actuators is described by a periodic spline. Variations in the control points cause changes in the shape of the curve and therefore in the actuator signals. An example for the encoding of the actuator signals is shown in Figure 17.

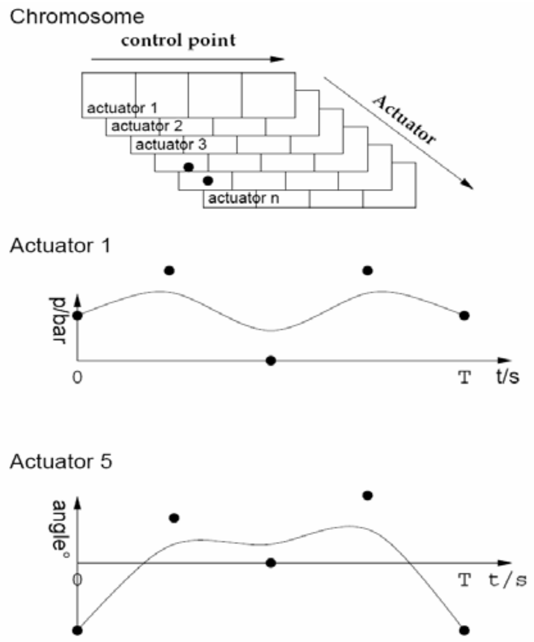

Figure 17: The chromosome is encoding a matrix of control points. The rows encode all parameter describing one single actuator. In the lower part of the figure an example of two different actuator signals based on the encoded control points is given. The number of control points is set to 5.

The x-coordinates of the control points correspond to fixed positions during the flapping period. The y-coordinates of the control points are the optimization parameters and are adapted during the evolution and cause changes in the actor signals and finally on the wing shape. The actuator signals for the Fluidic Muscles^{TM} (actuator 1-4) are interpreted as pressure and for the trailing edge (actuator 5-8) as angle in the interface to the wing model. In order to minimize the computational load during the online measurement the actuator values are calculated offline before starting the measurement and stored in a look up table.

Optimization Results

Experiments are performed with variations of the quality function and the optimization method used. The experimental results which are presented here are results of an optimization run minimizing the forces on the wing. For that reason the lift and drag forces of the wing are measured during the whole flapping period of the wing with a frequency of 100 measurements per second and summed up. In order to reduce the measurement noise the summation was done during two periods of movement. The wing profile is placed in such a way that the inflow angle of the flow is α = 6 degree. The flow velocity is set to v = 16 m/s. In order to estimate the noise generated by the measurement facility and the instationarities of the flow the quality variations were measured without any modification of the wing at first. The results are shown in Figure 18 indicated by the dark line. This noise level will determine the expected distance of the best solution to the absolute minimum of the quality value. The green curve shows the measured fitness during the optimization run. With a flapping frequency of λ_{wing} = 0.5Hz the measurement time for the whole optimization was about 30 minutes. It can be seen, that the quality value which is calculated by the forces on the wing is reduced during the optimization to about one third of the initial value. During the first 50 evaluations, which is equivalent to the first 10 generations of the evolution strategy the quality value is not decreasing. This is explained by the strategy parameter, which are adapted during this phase to sensible values. After that the quality measure is minimized by the optimization algorithm during the next 100 evaluations. Now, the measured forces are in a range of the measurement noise and no further progress can be possible.

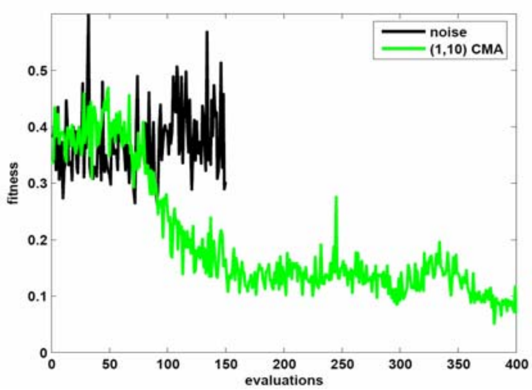

Figure 18: Measured quality of the initial design during 150 evaluations (dark) and the history of the fitness values during the optimization for 400 evaluations.

Summary

The article shows the design of an adaptive flapping wing, including the control, the implementation at a wind tunnel and the optimization of the shape of the wing profile.

The motivation was an optimization tool by Honda Research Institute that is able to handle several parameters during a duty cycle. The demonstrator has to be descriptive, not too complex, and not too expensive. So the idea was to build up a demonstrator that has the capability to imitate the bird flight. The wing of a bird is flapping, it can be twisted continuously and it has trailing edge flaps. The presented wing approximates all of these capabilities by four segments.

During the design process the first choice to activate the twisting was a piezo actuator driven tension-torsion coupling. This was a disappointment, because of the small strain of piezo actuators. By the means of the small strain, too large forces should have been generated and the piezo actuators would have become too big and expensive.

So Fluidic Muscles™ are used. They provide less force but much higher strain. The produced force is not large enough to twist the wing by the tension-torsion coupling, but it is large enough to twist the wing by a gear of flexure hinges.

The flexure hinges are designed to transform the longitudinal movement of the Fluidic Muscles™ into a rotational movement of the wing. Both, the Fluidic Muscles™ and the flexure hinge arrangements are small enough to fit into the small installation space of a NACA 0012 profile.

The movement of the trailing edge flaps is accomplished with small pneumatic round cylinders. Leverages and Bowden wires convert their longitudinal movement into an angular movement of the flaps.

The position of the twisting and the trailing edge flaps is detected by strain gages bonded to bending bars. A computer system consists of Matlab, Simulink and dSPACE is used to read out the data of the sensors, processing the data, optimizing the shape of the profile and to control the actuators. The optimization is done by an evolution algorithm that is also implemented in a Simulink model. The basic principles and strategies of this algorithm and the use to the flapping wing are shown. As example, one optimization is described, where a reduction to one third of the initial value is achieved.

Conclusions and Recommendations

The designed flapping wing is able to show the performance of the evolution strategy. Also it shows that is possible to significantly improve the air stream properties of an adaptive wing with a suitable optimization strategy in spite of limited dynamics and with a small range of variation. If the dynamics and the range of variation of the wing are further improved, it is also possible to improve the air stream properties. For a redesign the potential to improve the behavior of the adaptive wing is identified. One subject is the replacement of the valves of the Fluidic Muscles™. They exhaust the air to slow and so the flapping frequency is limited to 0.5 Hz. If faster valves are used, higher dynamics can be achieved. The reduction of the weight is an additional possibility of improvement. The fins are manufactured out of steel that could be replaced by GRP. This would improve the dynamics of the flapping mechanism, too. To improve the range of variation of the wing other actuators and/or gear mechanisms should be examined.

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