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ANALYSIS OF FLAPPING WING ROBOTS FOR PLANETARY EXPLORATION. AN EVOLUTIONARY APPROACH

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ABSTRACT

Comparing to usual flying mechanisms Flapped Wing flight is particularly interesting at low Reynolds regime, a situation where standard fixed wings and propellers have poor performances. The low density of some planetary atmospheres (e.g. Mars) often leads to such conditions. Flapping wing flight also uses the same surface for both propulsion and lift, allowing unprecedented manoeuvrability with vertical takeoff and landing capability.

Recent developments in computational fluid dynamics and mechanical modelling of insect wings allowed researchers to understand key mechanisms of insect flight. In this study we use a dynamically scaled model of a hawkmoth wing to investigate the influence of a larger number of motion parameters on overall flight performance. A robotic arm attached to the wing allows motion in three rotational axes. All six forces/torques are measured at wing base and recorded. This setup provides a large parametric search space which cannot be exhaustively explored in feasible time, for that matter Genetic Algorithm (GA) is used.

KEYWORDS: Robotic Insect, Flapping wing, flight dynamics, Genetic Algorithm, Planetary Probes

INTRODUCTION

Despite the potential applications, flapping wings pose a difficult problem for the present state of aerodynamics knowledge. The highly unsteady flow cannot be modelled easily. Only recently, when interest in using insect-like flight for space robotics or terrestrial applications emerged, engineers and biologists started to systematically approach this problem.

In 1996 Ellington et al. (ref. 6) performed fluid-flow experiments with a dynamically scaled insect wing, showing for the first time a vortex structure that could explain the high lift achieved by insects. Dickinson et al. (ref. 1) used a model of a fruit-fly wing in 1999 to explain other unsteady mechanisms that enable insects to fly. Some other researchers (ref. 2) tried CFD (computational fluid dynamics), and quasi-steady approximations, but up to now, there is no reliable method for predicting flapping wing performance either analytically or numerically.

Scaled fluid dynamic experiments are yet the best way available for estimating the flight characteristics in such

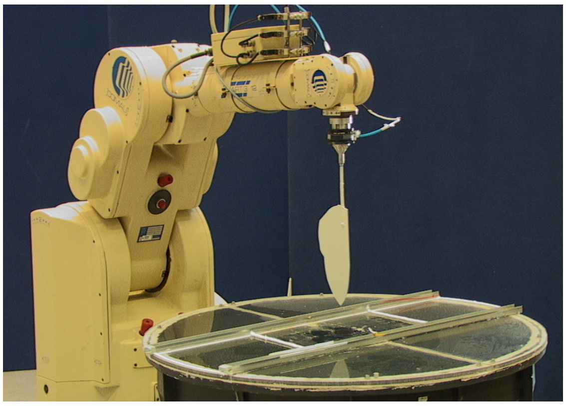

Figure 1: *View from the robotic setup with wing outside the water tank*

conditions. For that purpose we designed a flapping wing setup that allows optimization and probing of complex wing motion at Reynolds regime similar to possible planetary flying robots.

MATERIALS AND METHODS

The experimental rig consists of a robotically actuated wing immersed in a water tank, force sensors and a computer system.

For obtaining the Reynolds number of similar magnitude as a possible robotic flyer in a low density atmosphere such as in Mars, we move the test-wing much slower than in a real situation (about 0.3 Hz). We decided furthermore to immerse it in water in order to increase measurement quality. Being about a thousand times denser than air, water increases the reaction forces such that it can be measured by standard F/T sensors.

The robotic setup is capable of moving the model wing around three rotational axes. The movement in each axis is defined by 5 harmonics. Wing motion is accomplished by means of a "Smart 6.12" industrial robot from COMAU. The standard robot controller is usually accessible only at high level and programmed using PDL-2 language. Being primarily designed for industrial robots, it does not allow by itself the complex harmonic motion needed for the experiments. For that reason it was fitted with a special board (C3G open controller) that gives access to servo level, set-points.

The experimental rig is managed by two PCs. One of them runs MS-DOS 6.0 and is responsible for time critical robot servo control. This PC is directly connected to the C3G open controller, generating and sending joint set-point values every 20ms. The second

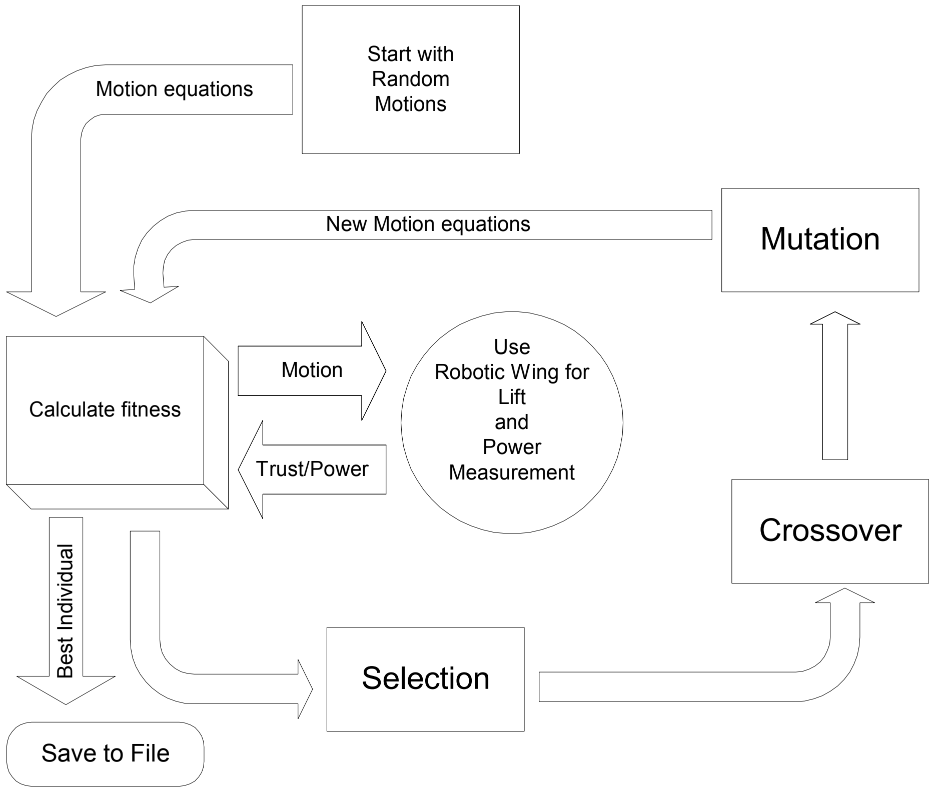

Figure 2 *shown the data flow related to the Genetic Algorithm optimization. Each individual in the population has 29 motion describing genes (29 real numbers) that are converted to wing motion, tested for power/lift, graded according to performance and fed-back to the GA computation. This ranking will affect the processes of natural selection, crossover and mutation. After which the new population is tested again, completing the cycle.*

PC runs Windows[tm] and performs all high level tasks, from Graphical User Interface and Genetic Algorithm processing to inverse kinematics, communicating with the DOS PC via serial line. This configuration combines the real time operation demanded by the robot controller with the power of online Genetic Algorithm optimization.

The wing is a 2mm tick aluminium plate cut in the shape of a halkmoth Mandruca Sexta wing. This shape was chosen for the Mandruca Sexta being one of the biggest flying insects, hence working at a Reynolds number range closer to the one we target; another advantage is that it has been well studied by other authors (ref. 6), allowing for easy result evaluation and comparison. The wing has a length of 30cm from base to tip, which allows for tests down to 15 000 Re.

All forces and torques acting on the wing base are measured by an ATI-Gamma 6-degree-of-freedom force/torque transducer coupled to a 12-bit DAQ. This allows for an accurate computation of power consumption, thrust intensity and direction at any time. Acquired data may be immediately used for fitness calculation in a Genetic Algorithm, or recorded on disk for further analyses.

The setup is designed to work in two distinct modes. It can be set to automatic GA optimization or testing of a preset motion pattern. When working at GA mode, it takes as input GA parameters like number of individuals in the population, mutation rate, weights for the fitness function and number of generations to be computed. It is also possible to choose the degree of complexity for the motion by setting the maximum number of harmonics that should be used, up to a maximum number of 5 per axis.

A real number based genome has been chosen for the implementation of the GA. Each one of the 29 real numbers (between -1 and +1) codes the magnitude of a different Furrier coefficient for the angular motion of each of the 3 axes. The fitness function is calculated based on the lift/power values measured from the hardware setup. Selection is based on the outcome of fitness function, such that the worse half of the tested individuals is eliminated in every run. The survivors crossover in couples with exponential probability, such that the best performing individual will have 50% chance of mating, the second 25% chance and so on until all the population is replenished. Mutation is achieved by adding a Gaussian noise to the genes on every run, the mean value is always set to zero, and the variance is set as the mutation rate, being configurable by the user.

EXPERIMENTAL PROCEDURE

The hart of any GA optimization is the fitness function. It describes the way in which a particular wing motion will be graded and decides if it is eliminated or left to reproduce itself and give rise to the next generation. In our experiment the fitness function is a simple weighted sum of produced lift and consumed power. The weighting factors are given by the user at the beginning of each run, and have a huge influence in the outcome.

This setup performs one test about every 30 seconds, so the number of individuals and generations should be chosen as to finish the experiment in usable time. A population of around 12 individuals appears to be enough

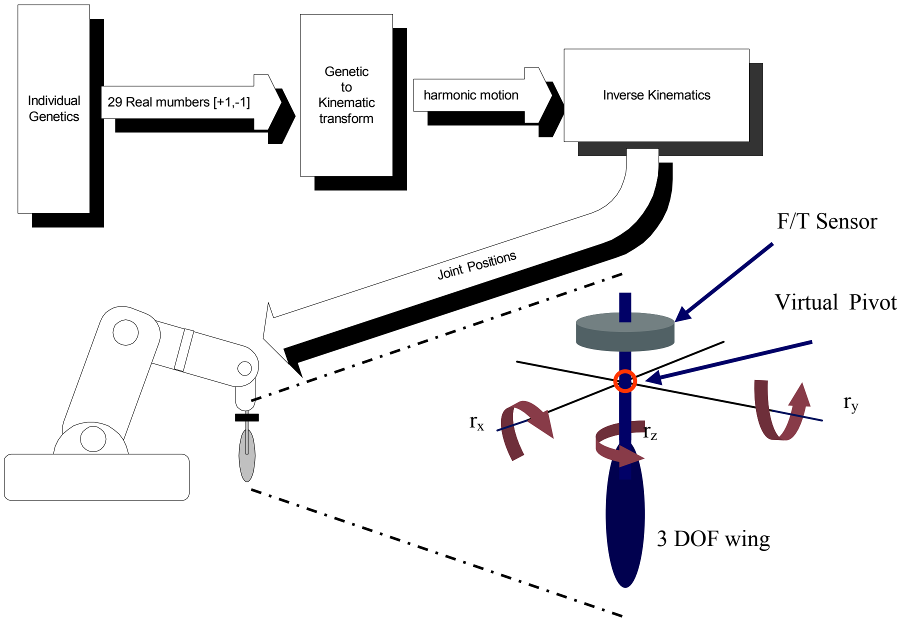

Figure 3 *shows the data conversion necessary to map the genome of each individual to actual wing movement. The genetic to kinematics mapping is processed in the Windows PC, outputting a stream of angular set-points for each of the 6 servos in the robot as to produce the corresponding wing movement. These set-points are then transmitted by serial line to the DOS PC that double checks it for safety and starts the actual motion.*

to have some diversity. The number of generations computed depends on the amount of time available, and on the judgement of the researcher whether further optimisation is still possible or worth it.

During the run of GA optimization the mutation rate can be changed manually, which is a very important feature. Mutation rate tells the GA how much chaos should be in the system. If a very low value is chosen, the change between generations is small, slowing down the evolution. High mutation makes fast evolution, but if it is too high the good traits acquired can be lost in the process. Increasing mutation rates manually in the course of the GA computation is a good way to escape local minima when the algorithm gets stuck. Lowering the mutation rate near the end of the computation allows the algorithm to fine tune wing motion.

It was observed in the first experiments that some individuals tend to move the wing backwards (trailing edge first). As wings are not generally designed to work that way, such mechanical stress could cause failure in a real flyer. Directly restricting wing mobility would narrow the GA freedom to search for patterns, so we decided to allow these unnatural movements. However, individuals are punished by charging an increased amount of power whenever it occurs. This quickly eliminated the individuals that insisted in this peculiar motion (they get often bad fitness, hence will hardly reproduce).

It was also found out that when starting the GA with full complexity (5 harmonics) and completely random individuals it was likely not to converge. Starting with a more natural wing movement (e.g. patterns known to work for some insects) solves this problem but also biases the GA results thereby avoiding more creative solutions. The chosen action was to start from random numbers, but with only one harmonic for each of the 3 axes (corresponding to a simple sinusoidal motion). This way the GA converged to an efficient pattern in just a few hundred generations. The simple one-harmonic individuals previously optimized are then used as a starting point for a more complex 2-harmonic optimization and so on, up to a full 5-harmonic run. This way we can guarantee that the results are not influenced by the user, while ensuring convergence in less than a thousand generations.

RESULTS

After a calibration phase in which known patters were used to check wing symmetry and to make minor adjustments to mechanical parts of the setup, the experiments began. The first results already showed how dependent the outcome was in respect to the weighting factors of the fitness function. When a high weight was placed for power saving, and not so high for lift production, the angle of attack had the tendency to become shallow, with little tendency to use unsteady mechanisms for boosting up lift. In the other hand, if a greater importance was placed in lift production the angle of attach could reach up to 50º incidence in some points, tending to an increased use of advanced wing rotation for production of lift peaks close to stroke reversal.

Some characteristics from the evolved patterns would be predictable and well explainable by the current knowledge in the field, such as the advanced flip (ref. 1). However, some quite unexpected features boosted the performance as well. One of them relates to oscillations in both stroke deviation and angle of attack. As shown in **Figure 4**b, these oscillations produce peaks of high lift in the middle of the stroke. A comparison of the original pattern with a manually modified one, with removed oscillatory component, shows some interesting results. The original one generated about 15% more lift for the same power and presented a superior repeatability in lift production. We could not find reports in literature about oscillatory behaviour naturally occurring in insect wings. Maybe it does not occur in nature at all, or it has just never been noticed. It could be possibly generated by strategic mass distribution on the wing, producing a small flutter. The small magnitude of the oscillations compared to wing stroke would anyway make it difficult to detect by direct observation.

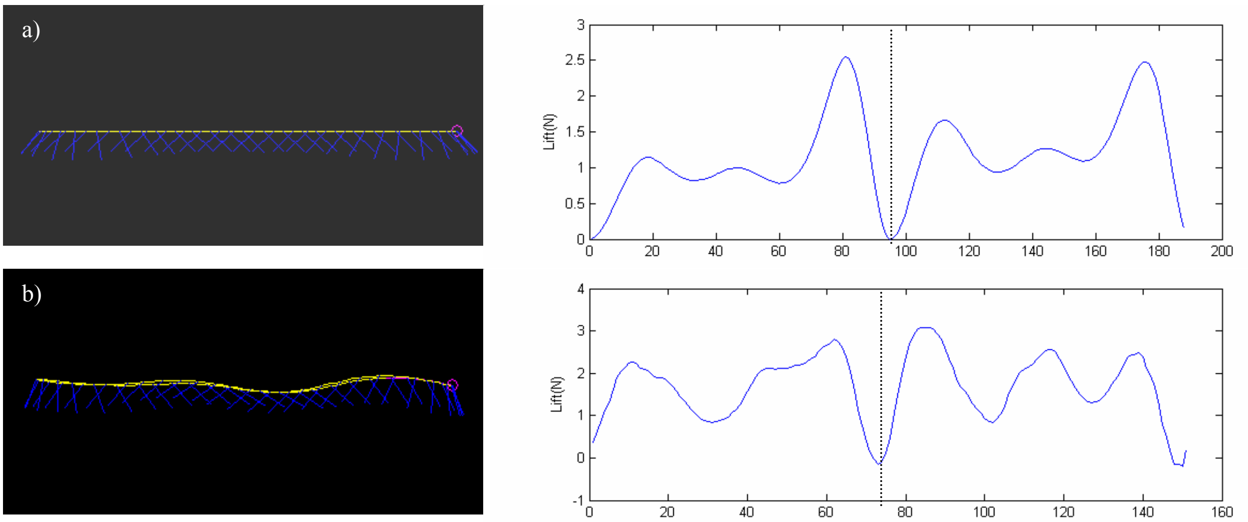

Figure 4 *shows one of the evolved patterns featuring some oscillatory behaviour b) compared with the same movement in witch the oscillatory behaviour were manually deleted a). The oscillations create force peaks in the middle of the stroke, boosting the lift in about 15%, and enhancing repeatability.*

CONCLUSION

The main achievement of the presented work was the implementation of an experimental test setup to study the complex problems involved in flapped wing flight.

Although the detailed studies are in the very beginning, some interesting results have been obtained. The GA was, for instance, able to evolve similar traits as the ones observed in real insects, like the advanced flip, which enhances lift production.

Some novel features were also found in the ongoing research. For instance the experiments showed that different targeted power to lift ratios give rise to specific flapping patterns. Oscillations in the wing rotation and the stroke plane were also discovered by the GA, causing an increase in the magnitude and repeatability of lift production.

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