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Inventing a Micro Aerial Vehicle inspired by the mechanics of dragonfly flight

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Abstract. Dragonfly flight is unique: Dragonflies can manoeuvre in all directions, glide without having to beat their wings and hover in the air. Their ability to move each of their four wings independently enables them to slow down and turn abruptly, to accelerate swiftly and even to fly backwards. We looked into the mechanics of the dragonfly flight and managed to transfer its flight dynamics into an ultralight flying object: the BionicOpter. With a wingspan of 63 cm and a body length of 44 cm, the model dragonfly weighs just 175 g. A brushless motor actuates the four wings and is used to alter the flapping frequency. Eight servo motors allow the amplitude and the twisting angle of each wing to be changed independently making the BionicOpter almost as agile and fast as its natural role model. Here we present how dragonfly flight dynamics can inspire future design of MAVs.

Key words:
bio-inspired engineering, biologically-inspired robots, aerial robotics, unmanned aerial vehicles, dragonfly flight

adfa, p. 1, 2011.

1 INTRODUCTION

Almost 300 million years ago dragonflies shared the land with early amphibians and the first reptiles. Some of the ancient dragonflies were enormously large. Meganeuropsis permiana reached a wingspan of up to 75 cm [2]. However, due to the decline in atmospheric oxygen levels during the Upper Permian Period and due to the evolution of birds, these giant dragonflies disappeared [2] and today's smaller but fast and agile dragonflies evolved. For the last 150 million years the body of the dragonfly has not changed much as shown in Fig 1. This consistency is only possible because dragonflies are optimally adapted to their environment and life conditions.

Fig. 1 Fossil of Aeschnogomphus intermedius. This dragonfly had a wingspan of 19 cm and was conserved in Solnhofen limestone for the last 150 millions of years. It was found in Blumenberg, Eichstaett, Germany.

Dragonflies are predators that catch their prey during flight and some even mate during flight. They live close to water which they need for egg deposition. There are about 6000 species of dragonflies with wingspans ranging from 18 mm to 190 mm. Their segmented body weighs less than 0.2 g, consisting of the head, the thorax with its six legs and a long abdomen. They have complex eyes that are perfectly adapted to fast visual perception during flight. The ability to move each of its four wings independently enables the dragonfly to fly in all directions and to execute the most complicated flight manoeuvers. Astonishingly, a wing weighs only about 0.002 g and has a thickness of 3 µ m at its thinnest point [3]. Yet dragonflies can reach a maximum speed of 54 km/h and with some tailwind they can fly up to 1000 km [4]. Some dragonflies even have been observed to fly with half a wing missing.

Dragonflies can slow down and turn abruptly during flight. They can accelerate swiftly and even fly backwards. Some dragonflies (Anisoptera) have broader hindwings that allow them to glide through the air. Finally and most importantly, dragonflies can hover in the air. Thus dragonflies can master all flight conditions of a helicopter, a plane and even a glider. This makes them a very interesting and unique biological role model for bio-inspired engineering. Hovering in particular is important for many real-world applications of micro aerial vehicles (MAVs), such as data collection in research, exploration of wind turbines or rescue missions.

Most interestingly, the dragonfly cannot only hover in the horizontal plane but is also able to hover in the vertical plane. With this function the dragonfly exceeds all common aerial vehicles including customary quadrocopters. Hovering in several positions allows for more degrees of freedom for the flying object when interacting with a second object in its surroundings and thus will lead to new applications of MAVs in the future.

The uniqueness of the dragonfly flight inspired us to look into the flight mechanics of real dragonflies and to turn their complexity into a technical reality. With BionicOpter we addressed this challenge. In this paper we describe the technical setup and give an outlook on how the dragonfly flight can inspire future MAVs.

Fig. 2 BionicOpter and its natural role model. On the left a natural dragonfly of the infraorder Anisoptera is displayed. These insects are characterized by the large multifaceted eyes that dominate the head, the four strong transparent wings and the elongated body. On the right the BionicOpter is displayed. BionicOpter was mostly inspired by the physiology and flight dynamics of Anisoptera, since these special dragonflies are not only able to fly extremely well, they can also hover in mid-air and glide.

2 Lightweight design with intelligent kinematics

2.1 The natural role model and bio-inspired engineerings

The mechanics of dragonfly flight are unique: Dragonflies can manoeuvre in all directions, glide without having to flap their wings and hover in mid-air. Most interestingly, they can hover in the horizontal plane and in the vertical plane. This becomes possible since they can control each of the four wings independently in amplitude and frequency. Further, they can twist their wings. To do this they use direct flight muscles, i.e. muscles that are directly attached to the joint of the wings. Each wing is moved by at least five distinct muscles. To control these muscles actively and precisely, and thus to define the position of the wing exactly, three to fifteen neurons innervate each muscle [5]. Finally, numerous sensors distributed across the whole body of the dragonfly deliver input about the position of each wing and the corresponding state of the environment.

We took inspiration from this highly complex system. However, we did not copy it one-to-one. Instead we combined the knowledge obtained from the real dragonfly, with newest materials, the latest technical inventions and with knowledge gained from other MAVs such as quadrocopters, and thus transferred the dragonfly dynamics to the technical world. This was only possible with a consistently lightweight design and by integrating the functions in the smallest spaces: sensors, actuators and mechanical components as well as communication and open- and closed-loop control systems are installed in a very small space and connected to one another.

The result is an MAV with flapping wing drive, encompassing thirteen degrees of freedom. A brushless motor in the bottom part of the housing provides the drive for the common beat frequency of the four wings. Each wing is individually twisted by one servo motor. One additional servo motor at the joint of each wing controls the amplitude. A linear movement in the wing root continuously adjusts the integrated crank mechanism to vary the deflection of the wing. The swiveling of the wings determines the thrust direction. The thrust intensity can be regulated using the amplitude controller. The combination of both enables the dragonfly to hover on the spot, manoeuvre backwards and transition smoothly from hovering to forward flight. The last four degrees of freedom are in the head and tail. The body of the dragonfly is fitted with four flexible muscles made of nitinol. These shape memory alloys (SMAs) contract when exposed to heat and expand when they cool down. Passing an electric current through the SMAs produces ultralight actuators that move the head horizontally and the tail vertically (See Fig. 3).

All of the motors, as well as the SMAs, the on-board electronics and the communication systems are actuated by two LiPo cells with 7.4 volts. While the motors and mechanic components are positioned within the housing the batteries are positioned in front of the housing to allow an easy and quick exchange. The batteries are covered by the head that nicely resembles the design of a dragonfly head. Furthermore, the whole design of the BionicOpter, especially the long and fragile tail closely follows the shape and design of the natural dragonfly.

In spite of its technical complexity the BionicOpter weighs just 175 g because of a consistently lightweight design and because of the fact that the housing, the tail, as well as the mechanical system were generated using laser-sintered polyamide and aluminium. Besides the low weight of the laser-sintering material, this technology allowed us to quickly generate new prototypes and to vary the wing position, the wing design etc. in just a few days. Besides polyamide and aluminium, other lightweight materials were used. Deep-drawn ABS terpolymer was used for the head and to cover the housing, while carbon-fibres and polyester membrane were used for the wings.

The final BionicOpter with a wingspan of 63 cm and a body length of 44 cm is almost as agile and fast as the natural dragonfly, not only because of its smart mechanics but also because of the on-board electronics and the accompanying software, which control the flapping frequency, amplitude and twisting angle. This way it becomes possible to control the BionicOpter with a digital spectrum transmitter via wireless remote control or even via a smartphone.

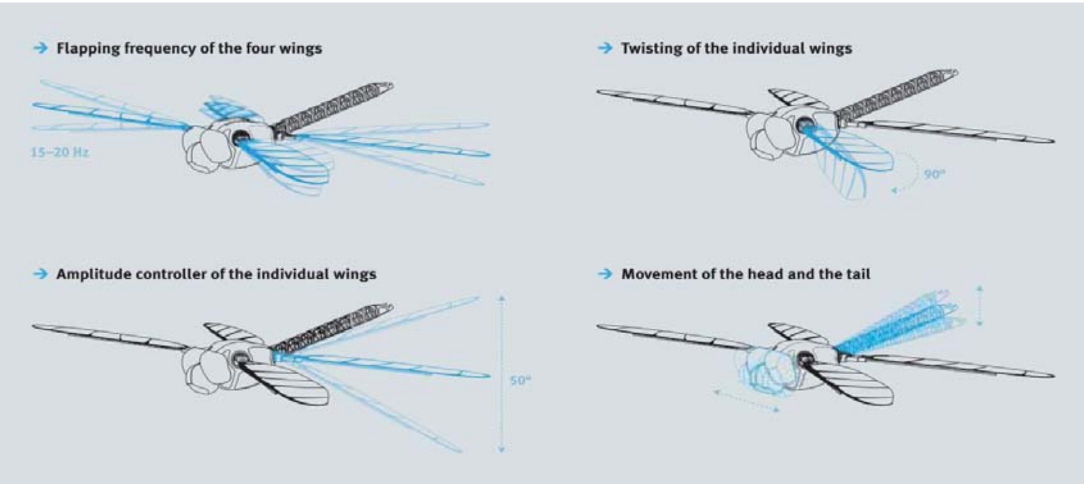

Fig. 3 Individually controlled wings. Just like the real dragonfly BionicOpter can control each of the four wings independently. One servo motor per wing controls the amplitude, another controls the twisting of the wing. Furthermore, the flapping frequency of all four wings can be controlled by the central motor and can be varied between 15-20 Hz.

2.2 Actuation of wings

As described above, dragonflies are such agile fliers because they can move their wings independently from each other. They can alter the frequency of the flapping, the amplitude of each wing stroke and the twisting angle of each wing. We reduced this complexity for space and weight reasons as well as to create a system that is easy to handle. One brushless VS external rotor serves as the main motor that actuates the flapping of all four wings. By altering the power of the motor, the frequency can be changed between 10 Hz the minimum necessary for stable flight and 20 Hz during acceleration. However, the final BionicOpter is easiest to handle when flapping at a frequency of about 15 Hz.

As Ratti and colleagues described [6], changing the frequency of an MAV with flapping wing drive can result in vibrations that decrease the energy efficiency, make the system hard to control and can even lead to damage the mechanical components when the vibrations build up. Here again we looked at the natural role model and how the dragonfly handles this issue. Real dragonflies only rarely move their forewings and hindwings in full synchrony (0° phase shift), i.e. all four wings beat up and down at the same time. Full synchrony actually only occurs during short phases of mating or hunting and is highly energy consuming [4, 7]. Moreover, dragonflies only rarely move their forewings and hindwings in an opposing fashion (180° phase shift), i.e. the forewings strike upwards while the hindwings strike

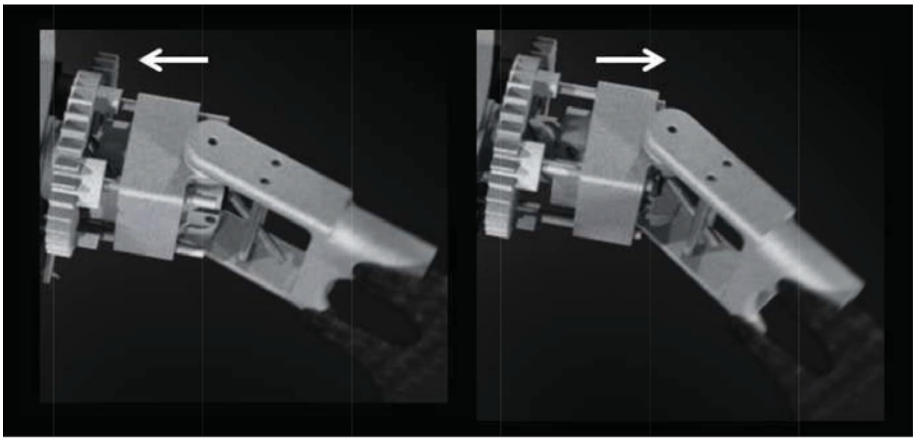

Fig. 4 Amplitude modulation. A crankshaft is used to convert the rotating movement of the motor (positioned outside of these image sections on the left) into an oscillating movement of the wing (lower right-hand corner of these image sections). The crankshaft leaves the housing containing the motor in a straight line. However, the distal part is tilted. The mechanical crosspoint can be shifted along the crankshaft as marked by the arrows using a servo motor. This enables the amplitude of the wing stroke to be modulated continuously (see animation for further details).

downwards. Mostly, the wing pairs move in a phase shift of 50° to 100°, which decreases energy consumption especially during forward flight. Most interestingly for natural dragonflies the hindwing leads this movement and is thus moved upwards slightly before the forewing follows.

Although the phase shift was an initial source of inspiration for the design of the BionicOpter, for our system we found that vibrations were reduced best when the forewing leads the movement. A phase shift of ~40° allows a stable flight both indoors and outdoors.

The main motor actuates the four wings using a crankshaft for each wing. This crankshaft is used to convert the rotating movement actuated by the motor into an oscillating movement of the wing. The interesting aspect of the crankshaft is that the proximal part of the crankshaft leaves the housing containing the motor in a straight line. However, the distal part is tilted. Since the position of the mechanical crosspoint can be shifted along the crankshaft from a more distal to a more proximal position the offset of the crankshaft changes and by this the amplitude of the wing movement changes (See Fig. 4). The movement of the crosspoint is actuated by a servo motor. The resulting deflection varies between 80° and 130°.

A second servo motor actively changes the twisting angle of the wing by up to 90 degrees.

Taken together, we can control the frequency of all four wings together, and the amplitude and twisting angle of each wing independently, resulting in 9 degrees of freedom. This way the direction of thrust and the intensity of thrust for all four wings can be adjusted individually, thereby enabling the remote-controlled dragonfly to move in almost any orientation in space.

2.3 Wing design

The movement of the wings of the BionicOpter resembles the wing movement of the natural dragonfly very nicely. Furthermore the design of the wings was inspired by the shape and structure of the wings of the real dragonfly.

Wings of dragonflies are highly fascinating. They only weigh about 0.002 g although they span a distance of up to 10 cm. The wings consist of a thin transparent membrane strengthened by a number of longituinal veins. Together with the crossconnections the veins form a beautiful pattern of cells. The front edge of the wing consists of much thicker veins with a thickness of up to 220 µ m. The rear edge measures only 3 µ m in thickness [3]. The front edge is thus much more rigid and stable than the flexible rear edge.

The same is true for the wings of the BionicOpter. They consist of a carbon-fibre frame enclosing a thin polyester membrane. Although the thickness of the carbonfibre is the same across the wing, the width, and thus the stiffness, varies. The front edge has an increased width that decreases towards the tip of the wings and further decreases towards the rear edge leading to a stable and rigid f ont edge and a flexible rear edge. Based on this structure the wings show a passive-torsion effect during flapping. While flapping up and down the base of the front edge leads the movement but the tip of the wing and the rear edge can move like the sail of a sailing boat and thus form a profile as known for rotor blades. This increases the thrust during flying. However, the point of the passive-torsion has to be located along the outer part of the wing. When the length of the wing is increased or when the frequency of flapping is increased this point of passive-torsion moves along the front edge of the wing towards the centre of the MAV. As soon as the point of passive-torsion passes the middle of the wing, the wing stops flapping up and down. Instead, it shows an effect comparable to a double pendulum and all of the thrust suddenly ceases. The same occurs when the stiffness of the wing is decreased. Thus the wings were optimized for stiffness to allow passive torsion but to prevent a double pendulum effect.

In addition we found that shorter wings made the BionicOpter easier to handle during flight manoeuvres since shorter wings can flap at a higher frequency. With a higher frequency tilting of the wings and amplitude changes of each wing stroke become more immediate.

We tested several wing lengths at different flapping frequencies. Furthermore, we stabilized the wing by inserting cross-sections as apparent in the wings of natural dragonflies. Different patterns of cross-stabilizations can be seen in Fig. 5 as well as the final wing layout.

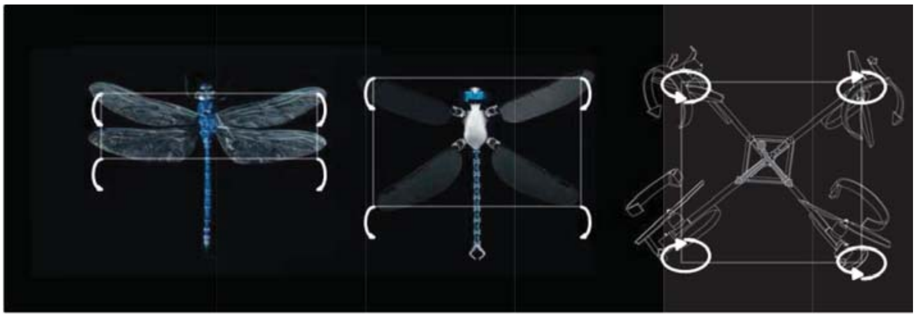

Fig. 6 Force distribution. On the left the natural dragonfly is displayed. The wings are almost parallel and the points of the main forces are positioned on the edges of an elongated rectangle. On the right a quadrocopter is displayed (picture from [8] adapted). The main forces are positioned at the edges of a square. We took inspiration from both and arranged the wings in an X-shape forming an angle of 30°. This made the final MAV easier to handle during flight.

2.4 Wing positioning

When the first demonstrators of the dragonfly inspired MAV were designed and tested, we positioned the wings in correspondence to the natural role model, i.e. parallel to each other, at a 90° angle relative to the sagittal plane of the body. However, this design of a MAV was hard to cont ol during flight. Here we decided to take inspiration from the technical world and looked at customary quadrocopters. Quadrocopters have four rotors. Each rotor generates a distinct momentum, which then sum up to yield the final force that makes the MAV fly. These four rotors are positioned at the edges of a square, since this positioning facilitates the corresponding calculations as well as the final handling of the MAV.

According to the design of quadrocopters we changed the positioning of the four wings of the BionicOpter away from a parallel position, by shifting the wings by 30°. Main forces generated by the four wings are thus better distributed and almost span across a square plane as valid for quadrocopters. When hovering with this wing positioning all four wings move forward and backwards in a horizontal plane instead of flapping up and down. The wings almost touch each other in front and behind the body, closing a 360° circle. This circle shows similarities in thrust generation with the circle spanned by the rotors of a helicopter. This clever design change made the MAV much easier to handle during flight.

3 Open- and closed-loop control on board

BionicOpter is a highly complex system. Yet, it is easy to operate using a digital spectrum transmitter or a smartphone. The flapping frequency, amplitude and installation angle are controlled by software and electronics; the pilot just has to steer the dragonfly. There is no need to coordinate the complex motion sequences. The signals from the remote control are transmitted via wireless modules.

During operation, the remote-control system transfers the signals that tell the object which direction to fly in and at what speed. A high-performance ARM microcontroler calculates all the parameters that can be adjusted mechanically based on the recorded flight data and the pilot's input. The processor actuates the nine servo motors to translate these parameters into movement using beat frequency, a swivel device and the amplitude controller.

In order to stabilize the flying object, data on the position and the twisting of the wings is continuously recorded and evaluated in real time during the dragonfly's flight. The acceleration and tilting angle of the BionicOpter in space can be measured using the inertia sensors. Furthermore, integrated position and acceleration sensors detect the speed and spatial direction of the dragonfly's flight.

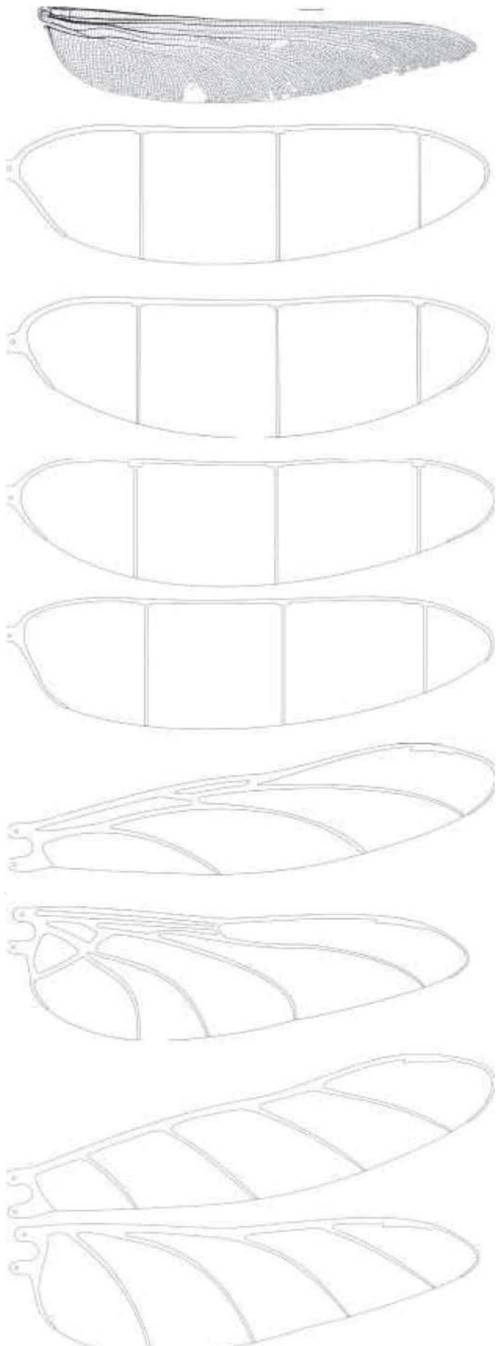

Fig. 5 Wing design. The drawing at the top is of a forewing of Megatypus schucherti ([1]) by Guenter Bechly showing the structure and the vein patterning of a dragonfly wing. We tested several different designs and lengths of wings, four of these designs are displayed here. The drawing at the bottom represents the final wing design resulting in a wingspan of 63 cm.

4 Findings for future MAV design

After bird flight had been deciphered with the SmartBird in 2011, dragonflies were the next-bigger challenge for us. Dragonflies exceed birds especially in terms of agility. Fascinated by this agility we studied dragonfly flight and managed to transfer the dynamics into an ultralight flying object: the BionicOpter. Like its natural role model BionicOpter can manoeuvre in all directions, accelerate swiftly and turn abruptly. Furthermore we were able to demonstrate that with such an MAV design it becomes possible to glide, to fly backwards and most importantly to hover in mid-air, even in different orientations.

Only with a consistently lightweight design and by integrating all functions in the smallest space, it was possible to make BionicOpter fly. Continuous recording and evaluation of the position and twisting of the wings in real time was necessary to stabilize the flying object. The findings about lightweight design, function integration and especially about continuous diagnostics to guarantee operational reliability and process stability will be transferred to industrial use in factory automation by Festo. The BionicOpter itself, however, will not be turned into a product but will be presented as a fascinating technology carrier. In this sense it can inspire researchers in two ways: in a technical sense BionicOpter can inspire future design of MAVs that are able to hover in different positions as its natural role model. In a biological sense, it can be used to better understand dragonfly flight.

Like a helicopter dragonflies can hover on the spot, they can fly up and down, forward and even backwards in this flight conditions. Unlike a helicopter, however, dragonflies do not need to tilt forwards to generate forward thrust. This means that they can accelerate while keeping a horizontal position. Further, they can hover in the horizontal plane but also in the vertical plane. With these functions dragonflies exceed every customary quadrocopter and can only be compared to the newest quadrocopters with slewing rotators (see [8] for an interesting technical setup).

Hovering in several positions allows for more degrees of freedom for the flying object when interacting with a second object in its surroundings and thus will lead to new applications of MAVs in the future. In research it could be used for data and sample collection. Because of the extreme agility such an MAV could easily pass between the narrow branches of a tree and reach e.g. a bird's nest. The MAV could quickly fly towards the desired position in the horizontal, plane-like mode then move into the vertical and hover in this position in front of the interesting spot, circle around it and take pictures from different angles and possibly even take samples. In line with this example, a possible industrial application is the exploration of wind turbines. The blades and the rest of the turbines have to be checked for damage on a regular basis. MAVs make it easy to approach the blades at high altitudes. A dragonfly-inspired MAV however, could examine the damage from different positions and different angles. Furthermore, with an attached tool, it could even repair or exchange small parts.

These are just some possible applications which can be solved with an MAV able to hover in different orientations. Dragonflies can do so very easily. Furthermore they can even fly in different orientations. This will open up further ideas for applications. With BionicOpter we showed that it is possible to transfer the flight dynamics of a dragonfly to the technical world. In this sense we hope that dragonfly flight will inspire the research community to think about the design of future MAVs in a new way.

Finally, and most interestingly, by studying BionicOpter further and by comparing it to real dragonflies, we can learn a lot about the incredible dynamics, the mechanics and especially the behaviour of the fascinating natural role model: the dragonfly.

Fig. 7 Different positions in space while hovering. With dragonfly-inspired MAVs it becomes possible to take different orientations in space while flying or hovering by twisting the four wings in regards to the body plane. Here the different wing positions during hovering are shown, when BionicOpter hovers in the vertical (upper picture) or horizontal (lower picture) plane. An intermediate state is shown as well.

Appendix

Videos showing BionicOpter's flight behaviour and an animation describing the actuation of the BionicOpter can be found here:
www.youtube.com/user/FestoHQ

Real-world recordings:
http://youtu.be/nj1yhz5io20
Animation:
http://youtu.be/JUAD7nhyzhU

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