ANALYSIS AND CONTROL OF A DRAGONFLY-INSPIRED ROBOT

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Abstract

Dragonflies demonstrate unique and superior flight performances than most of the other insect species and birds. They are equipped with two pairs of independently controlled wings granting an unmatchable flying performance and robustness.

In this paper it is studied the dynamics of a dragonfly-inspired robot. The system performance is analyzed in terms of time response and robustness. The development of computational simulation based on the dynamics of the robotic dragonfly allows the test of different control algorithms. We study different movement, the dynamics and the level of dexterity in wing motion of the dragonfly.

The results are positive for the construction of flying platforms that effectively mimic the kinematics and dynamics of dragonflies and potentially exhibit superior flight performance than existing flying platforms.

Keywords: robotic, bird, control, dynamic, aerodynamics.

1. Introduction

The study of dynamic models based on insects is becoming popular and shows results that may be considered very close to reality (Schenato et al., 2001) and (Wang, 2005). One of the models under study is based on the dragonfly (Tamai et al., 2007) because it is considered a major challenge in terms of dynamics. Recent studies show that the aerodynamics of dragonflies is unstable because they use a flying method radically different from steady or quasi-steady flight that occurs in aircrafts and flapping or gliding birds (Kesel, 2000). This unsteady aerodynamic has not received proper attention due to the inherent level of complexity.

Recently, technological advances allow the construction of robotic systems that are able to perform tasks of some complexity. In the past, there were significant advances in robotics, artificial intelligence and other areas, allowing the implementation of biologically inspired robots (Cohen, 2003). Therefore, researchers are investing in reverse engineering based on the characteristics of animals. The progress of technology resulted in machines that can recognize facial expressions, understand speech and perform movements very similar to living beings.

Some interesting examples are spiders (Vallidis, 2008), snakes (Spranklin, 2006), insects (Lauder, 2001) and birds (Ellison, 2006) (Couceiro et al., 2009a). They all require an extensive study of both the physical and the behavioral aspect of real animals.

The paper is organized as follow. Section two presents the state of the art in the area. Sections three and four provide an overview of the physical structure and the kinematics of the dragonfly, respectively. Sections five and six describe the dragonfly dynamics and the flight process implemented through the proposed model. Section seven and eight develop the dynamical analysis and the control algorithms, respectively. Finally, section nine outlines the main conclusions.

2. State of the Art

Inspired by the unique characteristics of animals, researchers have placed a great emphasis on the development of biological robots. This chapter addresses the studies and previous work done in this area focusing on the development of robots inspired in flying animals.

The flight of insects has been an interesting subject of, at least, half a century, but serious attempts to recreate it are much more recent (Zbikowski, 2005). Aircraft designers have been interested in increasing the morphic capabilities of wings and this area received a major boost in 1996, when the Defense Advanced Research Projects Agency of the U.S. (DARPA) launched a MAV of three years in order to create a flying platform with less than 15 centimeters long for surveillance and reconnaissance.

Some other biological inspired platforms have been developed such as the *Dragonfly* from *Wow Wee!* (Fig. 1). The *Dragonfly* toy was developed in 2007 and it is controlled by a radio transmitter. It looks like a dragonfly with a wingspan of 40.6 centimeters, with a lightweight body and strong double wings. As the dragonfly beats the wings to fly it does not need a propeller to generate a thrust force. It only uses a propeller in the tail to move left or right.
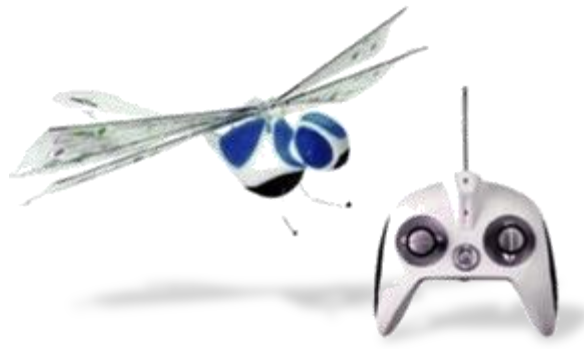

Fig. 1. Dragonfly from Wow Wee!.

In 2008 a robotic platform inspired by the flight of birds was developed at ISEC (Institute of Engineering of Coimbra). SIRB (*Simulation and Implementation of a Robotic Bird*) was built based on the results obtained using a simulator developed in *Matlab* (Couceiro et al., 2008).

While the developments of robotic platforms described above are a positive step in the production of new biologically inspired flying robots, there is a sub-area that does not have the proper attention of researchers: the control and autonomous navigation of robots.

Some studies have been appearing on the area of autonomous navigation of flying robots, studying new techniques of odometry and vision (Iida et al., 2001). Fumiya Iida developed control algorithms with the Reichard model conducting experiments in an autonomous flying airship robot in an unstructured environment (Iida, 2001).

The control of flying robots, even if not inspired in flying animals, represents a high level of complexity. Sukon Puntunan and Manukid Parnichkun (Pununan et al., 2006) compared the classical *PID* with a self-tuning *PID* algorithm for the control a small helicopter. The results obtained with the self-tuning *PID* proved that this type of control offers a better performance than the classical *PID*. However, it was possible to observe some relatively high overshoots in the system response.

In this paper we address another control and optimization methods comparing the results obtained in order to make the system steadier and, thereby, obtaining a better performance.

3. The Kinematics of the Dragonfly

The dragonfly model is being studied by some researchers due to the unique juggling maneuvers of this creature. Jane Wang (Wang, 2005) developed a set of equations based on a real model of a dragonfly by watching its flight in laboratory.

The objective in defining the geometry is to develop a physical model that can be mathematically described as being comparable to the actual real dragonfly. Based on some works already developed in this area, and performing a geometric analysis of the dragonfly, it was possible to reach a relatively simple model with a high-quality response when comparing to what it is observed in nature.

As we can see, the major difference between the geometry of two-winged animals (e.g, birds) and the geometry of the dragonfly are reflected in two pairs of wings.

Similarly to birds, the dragonfly also has several movements and flying styles. The flight capabilities of dragonflies are prodigious. In addition to the individual states of take-off, gliding and flapping, this last one is divided into four different styles due to the two pairs of wings: counter-stroking (where the front and rear wings beat with a delay of 180 degrees), phased-stroking (in which the wings beat with a difference of 90 degrees), synchronized-stroking (in which the four wings are synchronized as a single pair of wings), and gliding such as occurs in large birds. We will give special attention to the most common style in which the two pairs of wings of the dragonfly beat with a delay of 180 degrees (counter-stroking) that will be explained in the sequel.

Based on the geometry, and following an analysis of the multi-link model, we estimated the location of every joint in the robot and obtained the kinematic model represented in Fig. 2.
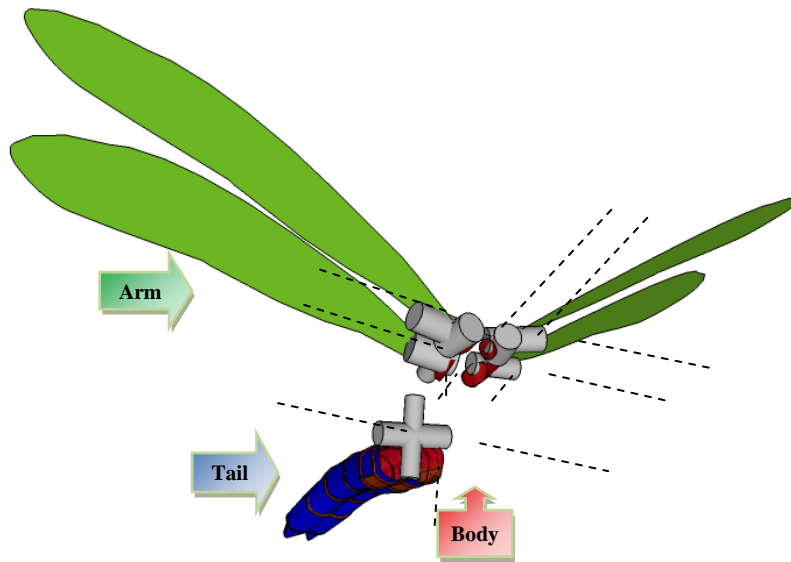
Fig. 2. Kinematic structure of the system.

The tail and each pair of wings have the same degrees of freedom (rotational) found in other flying models such as birds. The wings will be treated as a flexible link, similarly to what is seen in the nature, for minimizing the area of the wing when on the downward movement. This structure will provide a good mobility, making it a total of ten controllable links.

4. The Dynamics of the Dragonfly

The dragonfly dynamics is somehow similar to other flying creatures such as birds (Couceiro et al., 2009b) and, consequently, the same equations may be considered. Nevertheless, when it comes to the flapping flight, the dragonfly takes a great advantage over birds and other two-winged creatures (Fig. 3).
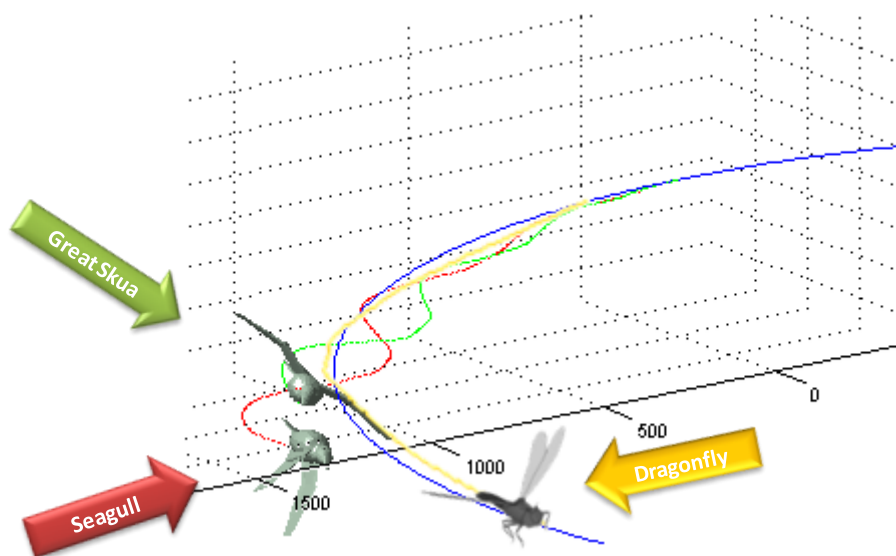

Fig. 3. Chart obtained through the developed simulator that shows the difference between the trajectory accomplished by a great skua (very large bird), a seagull (large bird) and a dragonfly. The stability of this last one when compared to the others is undeniable.

Recent studies reveal that dragonflies use a complex aerodynamics to fly, differently from aircrafts and large birds. A dragonfly flaps its wings to create a whirlwind of air that is controlled and used to provide lift. On the other hand, planes depend on good air flow over the top and bottom surfaces of their wings. For these machines the turbulence can be fatal. There are other creatures with a mechanism similar to the flight of the dragonfly, but with a higher level of complexity, such as the hummingbird, that can surprisingly manipulate the feathers of the wings during the rapid

flapping. However, the study of dragonfly flight shows that it can be as efficient as the hummingbird but with a much easier flight system. More than 200 million years of evolution provide evidences of a successful and infallible aerodynamics.

The two pairs of wings allow different independent flight techniques (as mentioned above) and the most common style is the counter-stroking. This type of flight allows that, when a pair of wings beats down creating a vortex of air, the other pair, which is still down, captures the energy of that vortex. Therefore, the air flow over the surface of the wings of the dragonfly has a much higher rate along the bottom of the wing creating more lift. In other words, the different states of flight, downstroke and upstroke, are indistinguishable creating an almost steady force positive to the movement and contrary to the weight. Nevertheless, applying this principle to the development of flying platforms is complex because the effect has to be simple and predictable. Less than ten years ago, people saw the flows generated by the insects as something uncontrollable. The turbulence was, and still is, often seen as something undesirable, causing failures in the turbines of the aircrafts and reducing their effectiveness. In the case of the rotor of helicopters, the blades sometimes fail because each blade is continuously affected by the turbulence generated by the preceding blade, causing vibrations that may weaken the metal. However, for the dragonfly, this type of flight is something natural and extremely efficient as we shall see in the next section.

5. Dynamical Analysis

We have undertaken a dynamical analysis to test the validity of the system model. In order to easily change the parameters (*e.g.,* wing area, weight) we built a computer program highlighting the fundamentals of robot mechanics and control.

The computer programs emphasize capabilities such as the 3D graphical simulation and the programming language giving some importance to mathematical aspects of modeling and control (Ferreira et al., 2000).

We start by presenting several results of the dragonfly dynamics around the gliding flight. These results are based on different parameters of the dragonfly. In each simulation the wind has a constant velocity of v = 5.0 m/s against the movement of the dragonfly that has an initial velocity of v_0 = 3.0 m/s. We change the weight and the area of the wing parameters in order to analyze the dragonfly dynamics. The initial parameters are a total weight of m = 10^{-3} kg and the wing an area of S = 10^{-4} m².

For the dragonfly to fly in a straight line, without flapping its wings, it is needed a continuously changing of the angle of attack (alfa) to keep a vertical resulting force equal to zero. The angle of attack will then increase the lift and the drag forces. A higher drag force results in the reduction of the velocity. This process stops when the velocity reaches zero since we do not want the dragonfly to be dragged by the wind.

In the following experiments that can be seen in Fig. 4-7 we will change the mass and the wing area in increments of 25% and 10% of the initial parameters, respectively.
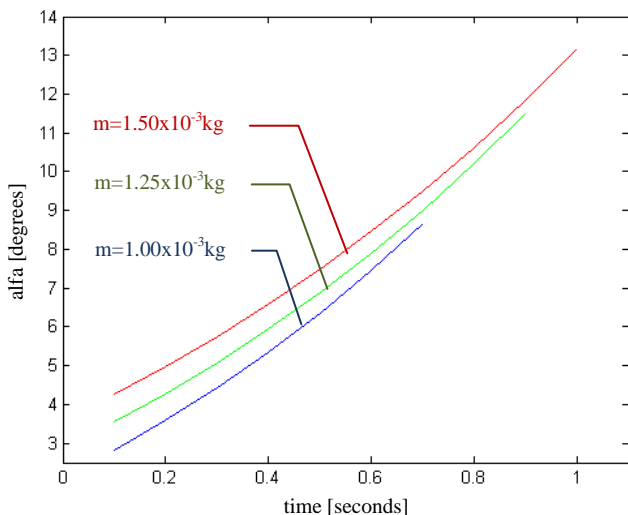

Fig. 4. Dragonfly gliding straight - changing the weight. Angle of attack versus time.
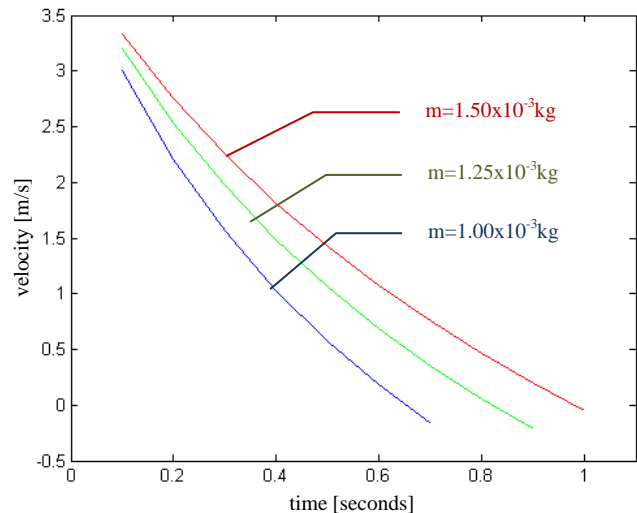
Fig. 5. Dragonfly gliding straight - changing the weight. Velocity versus time.

As we can see, increasing the weight requires a higher angle of attack in order to fly. The dragonfly keeps gliding for a short amount of time when compared to large birds. Despite the weight that is also well below the weight of the large flying creatures, like soaring birds, the area of the wings does not allow gliding for a long time. Obviously, the dragonfly, like all insects or small birds, does not have the same ability to glide as a large bird.

An interesting aspect is the fact that by increasing the weight of the dragonfly it can glide longer. This can easily be explained: if you throw a feather against the wind it will not go as far as if you throw a stone. As we increase the weight

of the dragonfly we are giving it the chance to fight against the wind more easily; however, we are also ensuring that it needs a higher angle of attack of the wings which, on the other hand, will eventually reduce the speed anyway.
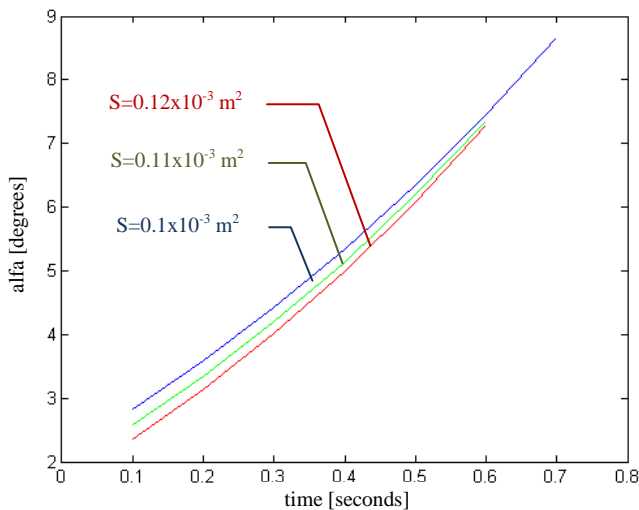

Fig. 6. Dragonfly gliding straight - changing the wing area. Angle of attack versus time.
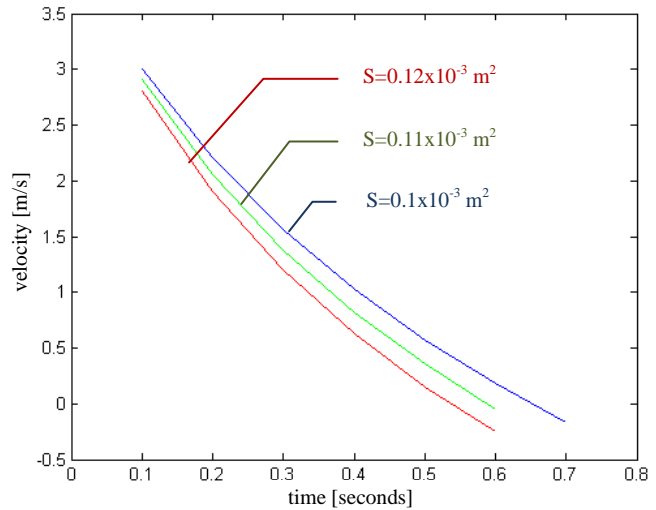

Fig. 7. Dragonfly gliding straight - changing the wing area. Velocity versus time.

By increasing the area of the wings the dragonfly does not need to significantly increase the angle of attack because it can keep gliding more easily (Fig. 6 and 7).

Birds, particularly large ones, adopt this technique much more frequently than insects do. Nevertheless, insects also use it, although not with the purpose of saving energy, since the difference is not relevant, but to accomplish some specific maneuvers.

The second experiment (Fig. 8-11) shows the horizontal (v_x) and vertical (v_z) velocities of the bird as well as the vertical distance obtained when the bird is gliding down a vertical distance of 5.0 meters, when considering a fixed angle of attack in both wings.
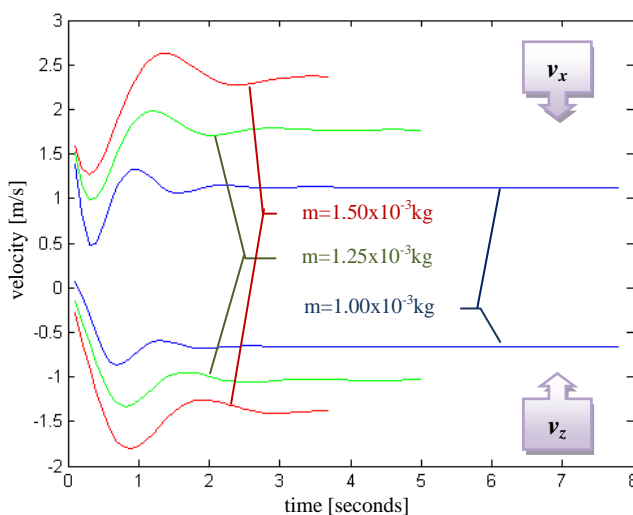

Fig. 8. Dragonfly gliding down - changing the weight. Angle of attack versus time.
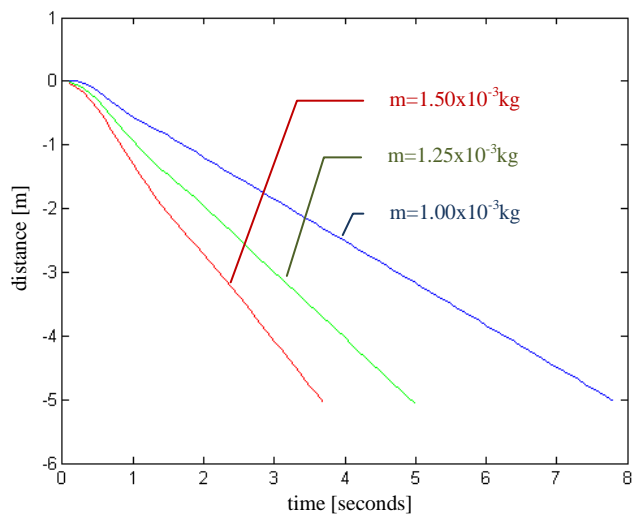

Fig. 9. Dragonfly gliding down - changing the weight. Distance versus time.

It is obvious that, when we increase the weight of the dragonfly, it reaches the desired vertical distance faster. However, there is a ubiquitous aspect that must be emphasized: the movement is much more linear than the movement of larger creatures such as birds. The reason is the relation between the area of the wings and the weight.

Let us compare the flight with the one of a large bird: while the wings of the dragonfly are, let us suppose, 100 times smaller than the wings of the bird, the weight of the dragonfly is about 400 times smaller. By doing this imbalance in the weight/area of the wings we assure that the flying movement is more linear. Based on what we just said and taking into account the large difference between the weight/area of the wings of the dragonfly, if we increase the area of the wing even more then the movement will be even more linear. We can confirm the idea in Fig. 10 and 11.
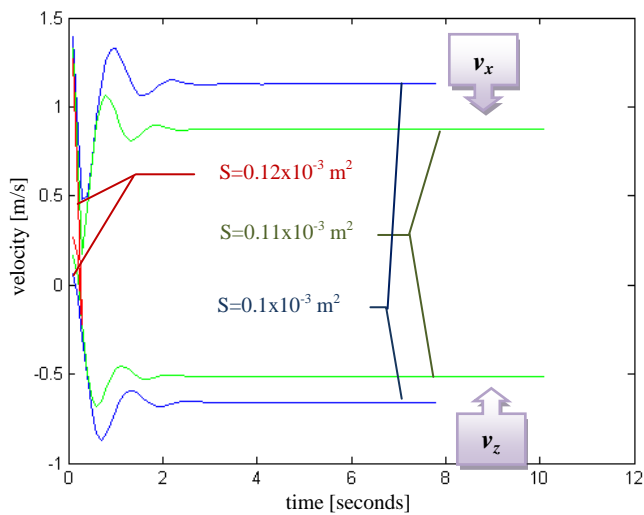
Fig. 10. Dragonfly gliding down - changing the wing area. Angle of attack versus time.
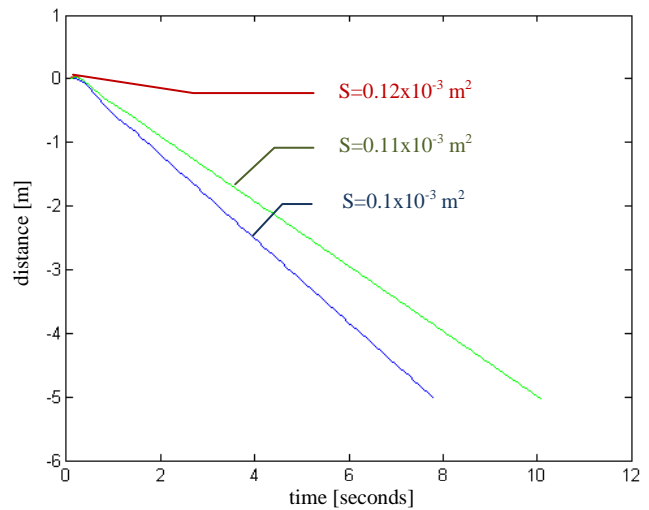

Fig. 11. Dragonfly gliding down - changing the wing area. Distance versus time.

Nevertheless, this relationship is not as straight as it seems in the previous charts. It is true that increasing the area of the wings by 10% the movement becomes more linear and it can eventually perform the desired trajectory smoothly and with a lower speed. However, increasing the area over 10% the dragonfly cannot achieve the desired position. This is due to the fact that the size of the wings are so large, when compared to the weight, that the drag caused by the wings is too high so that the resultant force in x-axis reaches zero.

This shows that the relationship weight/area of the wings of the dragonfly is ideal, and that manipulating this relationship can eventually have unexpected results and may compromise the good efficiency of the dragonfly flight.

We will now analyze the flapping flight of the dragonfly to understand how it works in order to implement a control algorithm. The analysis of the flapping flight is not as simple as for the case of the gliding flight. In the next experiment, we must note that our first priority is to fly in a straight line.

Following a similar line of thought of the gliding flight we change the weight and wing area. Fig. 12 and 13 show how the velocities and vertical distance react while changing the bird weight.
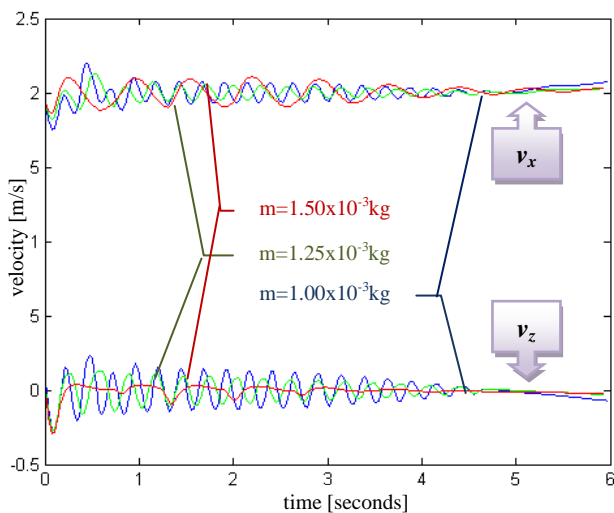

Fig. 12. Dragonfly flapping straight - changing the weight. Angle of attack versus time.
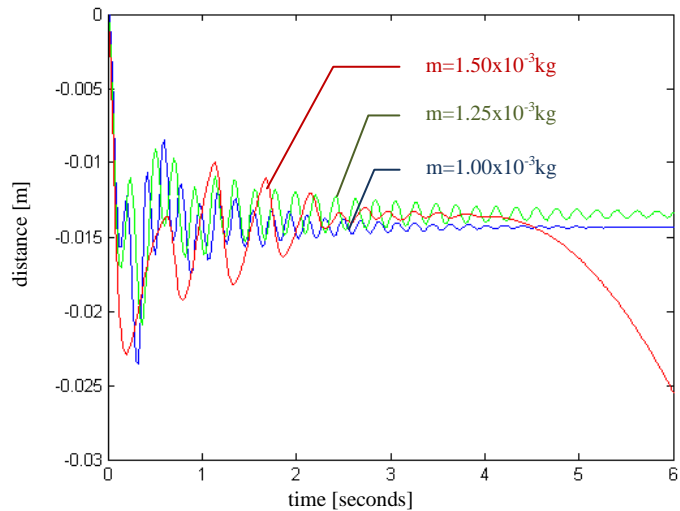

Fig. 13. Dragonfly flapping straight - changing the weight. Distance versus time.

The previous figures shows that the dragonfly can maintain a very straight trajectory except for a weight 50% higher, because as it begins to slightly lose some altitude. However, the flight starts with an initial velocity $v_0 = 2$ m/s and remains near this value even with the significant increase in the weight.

It is easy to understand that, if we increase the area of the wings of the dragonfly (Fig. 14 and 15) then the flapping wings response will be enhanced. This effect is opposed to the previous experiment, where the significant increase of the area

of the wing brought some inconvenient in the gliding flight, because of the lack of thrust force. A larger area of the wings means a smaller settling time of the dragonfly velocity as can be easily seen in Fig. 15.
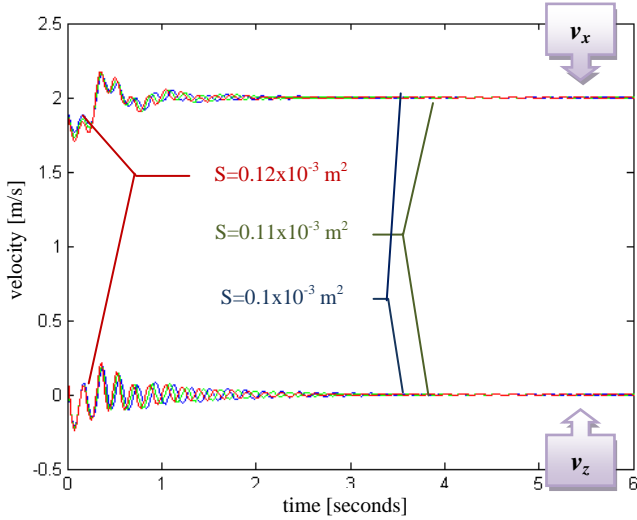

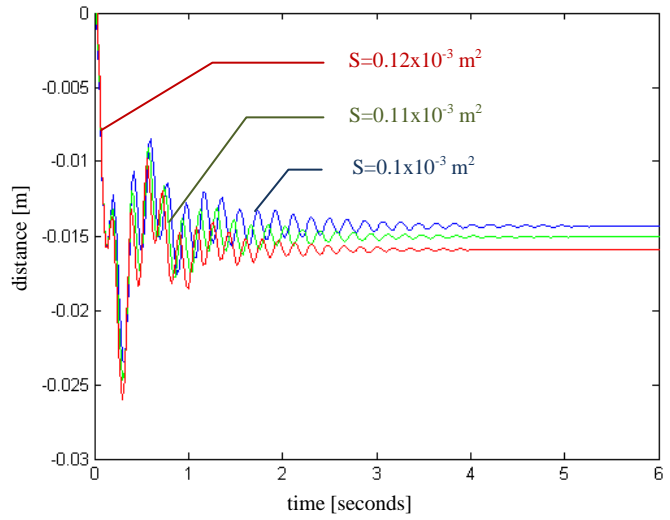**Fig. 14. Dragonfly flapping straight - changing the wing area. Angle of attack versus time.**

Fig. 15. Dragonfly flapping straight - changing the wing area. Distance versus time.

The difference of effectiveness between the dragonfly and large birds mainly focuses on the flight stability. The dragonfly can eventually overcome variations in the parameters (e.g., weight, area of the wings) more easily than birds and other two winged creatures. The dragonfly maintains a regular wing-beat of 3.0 to 5.0 flaps/s (depending on the weight and wing area) not making use of the gliding flight such as large birds do. The experiments in the next section with the optimized controllers will give us a better understanding about the real stability and performance of the dragonfly flight.

6. Controller Performances

In this section we develop several experiments for comparing the performances of the *FO* (Fractional Order) *PID* algorithms (Ferreira et al., 2002) (Couceiro et al., 2009c).

FO controllers are algorithms whose dynamic behavior is described thorough differential equations of non integer order. Contrary to the classical *PID*, where we have three gains to adjust, the *FO PID*, also known as *PI^λD^μ* (0 < λ , μ ≤ 1), has five tuning parameters, including the derivative and the integral orders to improve de design flexibility.

The mathematical definition of a derivative of fractional order α has been the subject of several different approaches such as the Laplace: The Grünwald-Letnikov definition is perhaps the best suited for designing directly discrete time algorithms.

$$D^\alpha[x(t)] = \lim_{k \to 0} \left[\frac{1}{h^\alpha} \sum_{k=1}^{\infty} \binom{\propto}{k} x(t - kh) \right] \tag{1a}$$

$$\binom{\propto}{k} = \frac{(-1)^k \Gamma(\alpha + 1)}{\Gamma(k + 1)\Gamma(\alpha - k + 1)} \tag{1b}$$

where *Γ* is the gamma function and *h* is the time increment.
For the implementation of the *PI^λD^μ* given by:

$$G_c(s) = K \left(1 + \frac{1}{T_i s^\lambda} + T_d s^\mu \right) \tag{2}$$

we adopt a 4th-order discrete-time Pade approximation.

To tune the controllers' parameters we used a medium scale *Gradient Descent* method with 200 maximum iterations. To find a local minimum of a function of the position error using gradient descent, one takes steps proportional to the negative of the gradient (or the approximate gradient) of the function at the current point.

The first attempt to control our system will be changing the wing speed velocity, angle of attack and tail rotations accordingly with the cartesian position error.

In order to study the system response to perturbations, during the contact we apply, separately, rectangular pulses, at the references. Therefore, the trajectory used to optimize the controllers consists in a straight line flight with a velocity of v_x = 1 m/s during the first 20 seconds. The dragonfly will then need to instantaneously achieve a velocity of v_x = 3 m/s. Finally, 20 seconds later, the system will instantaneously reduce is velocity to v_x = 1 m/s again.

In this optimization it is unnecessary the use of a controller in the y-axis since there will be no movement in this axis; therefore, we will ignore it for now.

Let us then compare the *PID* and *PI$^\lambda$D$^\mu$* controllers. Under the last conditions we obtained the *PID* and *PI$^\lambda$D$^\mu$* controller parameters depicted in Table 1.

Table 1. PID and PI$^\lambda$D$^\mu$ controller parameters

	K_{pX}	K_{iX}	K_{dX}	μ_X	λ_X	K_{pZ}	K_{iZ}	K_{dZ}	μ_Z	λ_Z
PID	60	0	13	-	-	125	65	25	-	-
PI$^\lambda$D$^\mu$	36	0	5	0.85	0.9	106	70	25	0.8	0.6

To analyze more clearly the dynamical response to the step perturbation we subtract the dynamic response without perturbation. Fig. 16 depict the system response under the action of the *PID* and *PI$^\lambda$D$^\mu$* algorithms.
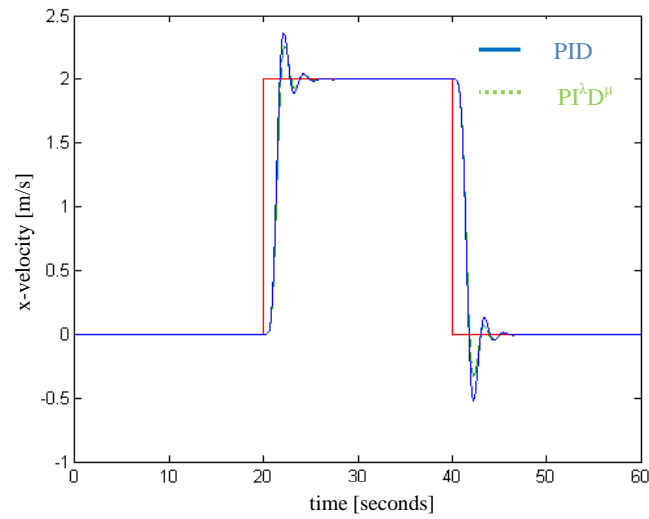

Fig. 16. Time response of the system under the action of the PID and PI$^\lambda$D$^\mu$ controllers.

Table 2 compares the time response characteristics of the integer and the fractional *PID* controllers, namely the percent overshoot *PO*, the rise time t_r, the peak time t_p and the settling time t_s.

Table 2. Time response parameters of the system under the action of the PID and PI$^\lambda$D$^\mu$ controllers

	$PO(\%)$	t_r	t_p	t_s
PID	18.25	20.74	21.16	25.52
PI$^\lambda$D$^\mu$	13.16	20.86	21.26	25.58

We can see that the *FO* algorithm takes advantage in the time response analysis, with a significant reduction of the overshoot.

7. Conclusion

The functionalities presented in this work are implemented in a simulation platform. We obtain satisfactory results proving that the development of the kinematical and dynamic model can lead to the implementation of an artificial machine with a behavior close to the dragonfly.

The design methodology and implementation can be deemed successful in this project. By obtaining a balance between physical modeling and the objective of animation, a strong advance in the system design has been achieved. Despite all simplifications, our model is still incomplete, and further research needs to be conducted to explore additional abstractions.

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