An Insect Flight as Non-Holonomic System

Abraham Rojano[1], Raquel Salazar[1], Irineo López[1], and Fernando Rojano[2]

[1] Universidad Autónoma Chapingo Km 38.5 Carretera México-Texcoco Chapingo, Edo. de México, C.P 56230,
Mexico
[2] Faculty of Biosystem Engineering,
University of Arizona, Tucson AZ, 85712
USA
abrojano@hotmail.com

Abstract. Nowadays, with currently available computational resources, it is possible to tackle complicated problems of not linear type. The specific case of the flight of an insect is not the exception, and although the problem is extremely daily, it can be an excellent testing to show the involved spatial and time trajectories not only as an elegant challenge but also serves to illustrate the process of abstraction by assuming appropriate hypothesis and using elements of the classic mechanics, in order to yield into the solution process. Based on Newton-Euler equations with four primary variables like position of the insect, horizontal and vertical velocity, angle, and angular velocity the simulation of longitudinal flight is carried out. These simulations consider the effect of different velocities of the air and also different angles of attack. Finally, for the nonlinear time invariant system there is a 3D plot showing patterns in how the position of the insect is changing with reference to the other three variables considered in the system.

Keywords: Computational, Newton-Euler, Velocity, Pattern.

1 Introduction

Nonholonomic systems are studied from the Euler times in the 18th century, and they are mainly concerned with frictionless problems corresponding to motion of rigid bodies. Euler, Lagrange and Hamilton point of views are commonly linked by means of Poisson brackets, however by using special constraints in position or velocity requires generalizations preserving the energy system, it requires the combination of experiments, mathematics, and computation, in order to simulate different scenarios. Even though, conservation laws in biology are difficult to identify, it is possible to assume that insects are somehow symmetrical as well as its body is made of rigid segments subject to assumptions of potential flow surrounding the insect. Similarity with the studies of aircrafts navigation like airplanes or helicopters, as well as its numerously industrial applications, nonholonomic systems enhance and motivate exhaustive simulations in order to control by determining the ranges of stability. Furthermore, adapting aircraft stability to the flight of insects should be made by

Advances in Soft Computing Algorithms
Research in Computing Science 49, 2010, pp. 39-46

means of forces produced with the wings flapping. This implies that insects follow a particular dynamics beyond the simple geometry and kinematics, so this work involves a living system with wings subjected to the total force and/or moment produced [1].

Although, any insect follows similar flights or patterns, it is easily and quickly observed that size, shape, and weight are sufficiently different to be impossible achieve a realistic representation and general solution. Under these circumstances, we are starting to explore possibilities to simulate a flight of a particular locust [2]. In the first part, it is developed a methodology to log a set of data from experiments which are going to be used in a set of equations to reproduce a flight under a linearized model [1]. This set of data includes some properties like size, weight, moment of inertia, and forces produced by flapping.

1.1 Main Characteristics of the Locust

As the model is determined by physical properties of the locust, then it is important to cite some of them. For example, to have an idea the wing beat frequencies of the largest butterflies is around (c. 40 rad/s in the $1 \times 10-3$ kg birdwing Troides rhadamantus) which is comparable to the rotor frequencies of the smallest helicopters (44 rad/s in the 2×103 kg Eurocopter Bo1054) [3].

The desert locust is a robust, migratory, four-winged insect of 0.1m span, optimized for endurance, rather than maneuverability, and with a range of several kilometers at its cruise speed of 4 m/s. Although locusts do not vary in overall body plan, different individuals vary markedly in size. The wings beat at c. 20 Hz, with the hindwing leading the forewing by $\pi/6$ rad. The hindwing typically sweeps 110° through every half-stroke, while the forewing sweeps through 70°. The hindwing comprises a collapsible fan consisting of a flexible membrane with supporting ribs radiating from the root. Each wing is moved by 10 muscles, and with no separate control surfaces, flight control is made by changes in the wing kinematics. Slower flight control is made by moving the legs and abdomen, which act as a rudder and also shift the center of mass. Locusts are equipped with a range of sensors known to be used in correctional flight control. The antennae sense airspeed, analogous to a Pitot tube. Wind-sensitive hairs on the head sense aerodynamic incidence. Each wing has at its base strain receptors involved in flight control that may measure total wing loading, but perhaps more likely monitor wing kinematics: they have no direct or functional analogy in conventional aircraft [3].

From observations of biologists it is pointed out that compound eyes works as horizon detectors measuring bank and pitch angle, and as optic flow detectors measuring heading and perhaps pitch, roll and yaw rate. Additionally, locusts are not known to have any sense of gravity in flight. Although vision is certainly important in insect flight control, it cannot give absolute measurements of bank and pitch angle unless referenced to gravity, and is ambiguous in respect of certain aspects of self-motion [3].

1.2 Newton-Euler Equations

To simulate the flight, this framework is going to be based on the set of equations of Newton-Euler obtained from the general principles of lineal and angular momentum conservation, respectively.

$$\begin{aligned} \dot{u} &= -wq + \frac{X}{m} - g\sin\theta \\ \dot{w} &= uq + \frac{Z}{m} + g\cos\theta \\ \dot{q} &= \frac{M}{I_{yy}} \\ \dot{\theta} &= q \end{aligned} \tag{1}$$

From this set of equations is important to say that simulation is going to consider a 2D simulation flight, longitudinal with respect to the insect. Formally, u and w are the velocity with respect to the horizontal and vertical axis z, correspondingly, q means the angular velocity with respect to the center of mass and θ is the angle with respect to the horizontal axis, as shown below in Fig1.

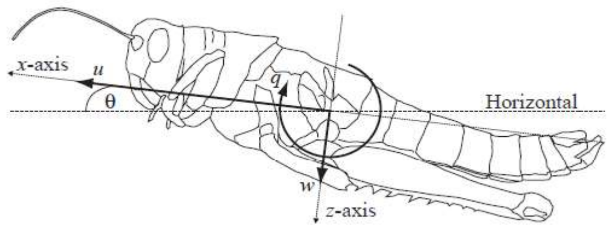


Fig. 1. Diagram of a two dimensional insect section.

2 Objectives

- To identify what are the most important factors affecting stability of insect flight.
- To develop a simulation program for nonlinear conditions identifying the central core data.

3 Methodology

There were several concerns regarding to data obtained from experiments. Basically, attending needs of the Newton-Euler equations some values as the weight, moment of inertia and forces should be as accurate as possible. Considering three types of locusts some data were considered in the simulation and that information can be summarized in Table 1 [1]. Although, in Table 1 considers three type of locust, considering simulations for the locust type “R”, “B”, and “G”.

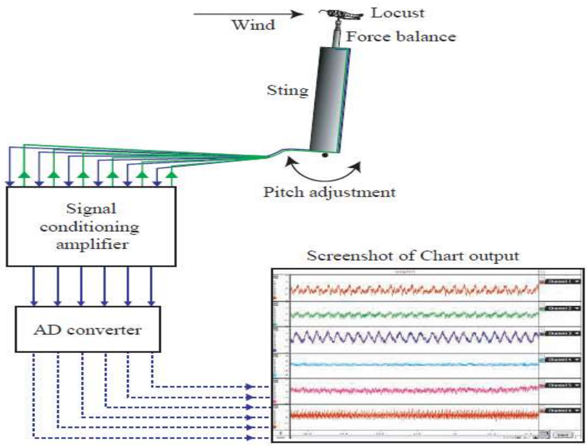


Fig. 2. Experimental setup for recording forces from a locust.

3.1 Logging forces

Logging forces are important since they are the reference in the simulation, for analyzing stability and forces. Essentially, a locust was attached to the top of a needle. That locust was inside of a wind tunnel (see Fig 2) and the forces were recorded at different wind speeds and also at different position of the insect (angle with respect to the horizontal axis). Forces were recorded in an interval from 2 to 5.5 m/s and also at angles from 0° to 14°; these ranges were given from observations when the locust is found in a free flight [1].

4 Results

Once forces were recorded, it was needed to preprocess data. This preprocess implies that was done a simplification of forces variability to one representative flapping. This means that there is an assumption that flapping is uniform during the flight and one period of flapping is going to be exactly equal to the next one; which it does not occur in a real flight but it reduces the set of data significantly. Then, data obtained from experiments, where variability of forces for one cycle of flapping (X correspond to the horizontal direction) at different angles of the locust (from 0° to 14°).

Data recorded include thousands of points difficult to handle, to overcome this situation was used standard Fourier series in order to reduce into a few coefficients corresponding to eight harmonics.

Forces in the horizontal and vertical directions were reproduced at different angles and moments for various wind speeds and appropriate references and right connections. With this new set of tools was looked for the quasi-static equilibrium in order to start simulations for quasi-static conditions with Runge-Kutta methods provided by Matlab toolbox as ode45 function.

One way to analyze performance of the model is considering a small perturbation in one value of the initial conditions in a linear time periodic model (LTP). For instance, horizontal velocity (u) is perturbed by a small value of 0.002 m/s during 0.4 s corresponding to 8 cycles of flapping) were it was found that among three types of locust follow the same pattern. These simulations consider average of the forces during one cycle of flapping, even more nonlinear time periodic (NLTP) models include force variations. NLTP model considers forces in Fourier series fitted until the eight order of harmonics. This covers variability of either forces or moments during one cycle of flapping, with initial conditions equal to the quasi-static equilibrium. Table 1 provides information regarding the physical and geometric characteristics of three type of locust, considering simulations for the locust type “R”, “B”, and “G”.

Table 1. Reference values for three types of locust.

Locust	Reference body mass (g)	Reference body length (mm)	Moment of inertia Iyy (10-9 kg/m2)
“R”	1.8490	46.0	232.8
“G”	1.4357	40.5	140.3
“B”	1.8610	46.0	236.0

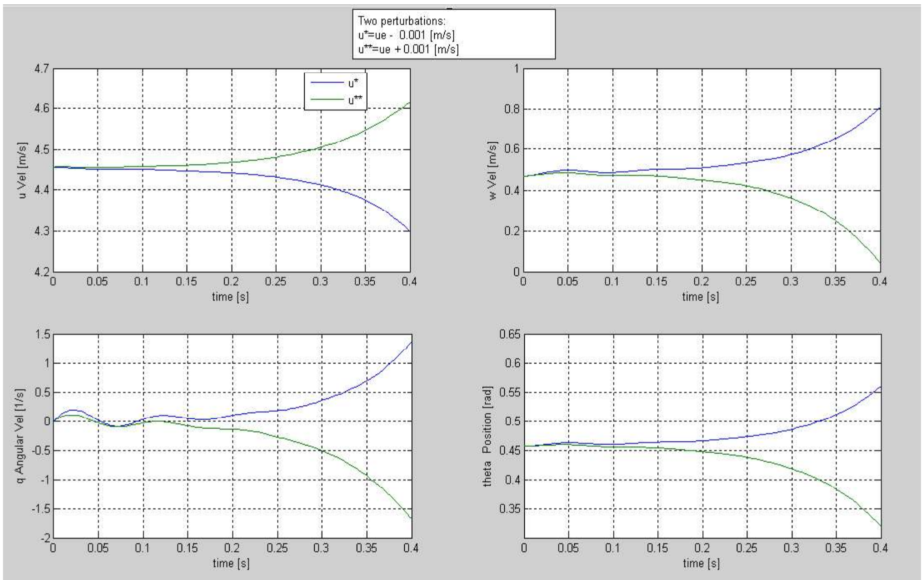
Table 1 provides information regarding the typical angles and velocities used for three locusts.

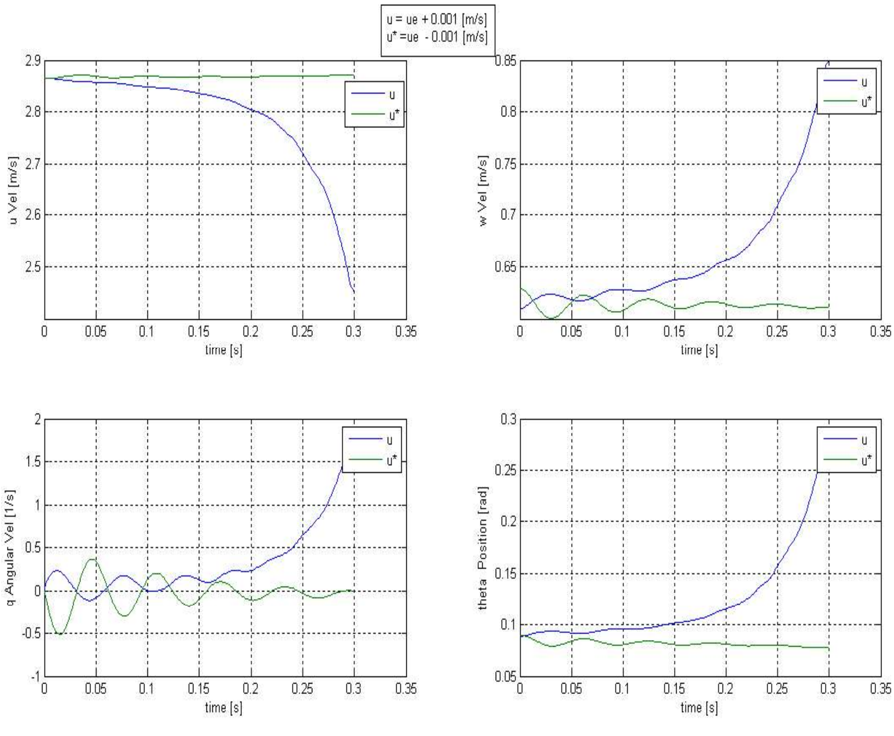
Table 2. Conditions for quasi-static equilibrium of each locust.

Locust	θ(deg)	α(deg)	U(m/s)
“R”	26	6	4.48
“G”	5	12	2.93
“B”	23	9	4.79

The simulations were made by perturbing the horizontal velocity, with initial time modified by 0.025s as equivalent to a half cycle of flapping. This perturbation accomplishes the idea of how much would change a possible trajectory of the flight because starting of flapping with open wings instead of closed wings (when initial time is equal to zero).

The simulated final path is completely different for locust type “R” because of different initial times. In the same way in Figure 12 there is a similar result. However, in Figure 11 which corresponds to locust type “G”, there is a parallel path for the four variables. This situation may tell that this type of locust might be stable.


Two perturbations:
u*=ue - 0.001 [m/s]
u**=ue + 0.001 [m/s]
u*
u**
u Vel [m/s]
w Vel [m/s]
q Angular Vel [1/s]
theta Position [rad]
time [s]


u = ue + 0.001 [m/s]
u* =ue - 0.001 [m/s]
u
u*
u Vel [m/s]
w Vel [m/s]
q Angular Vel [1/s]
theta Position [rad]
time [s]

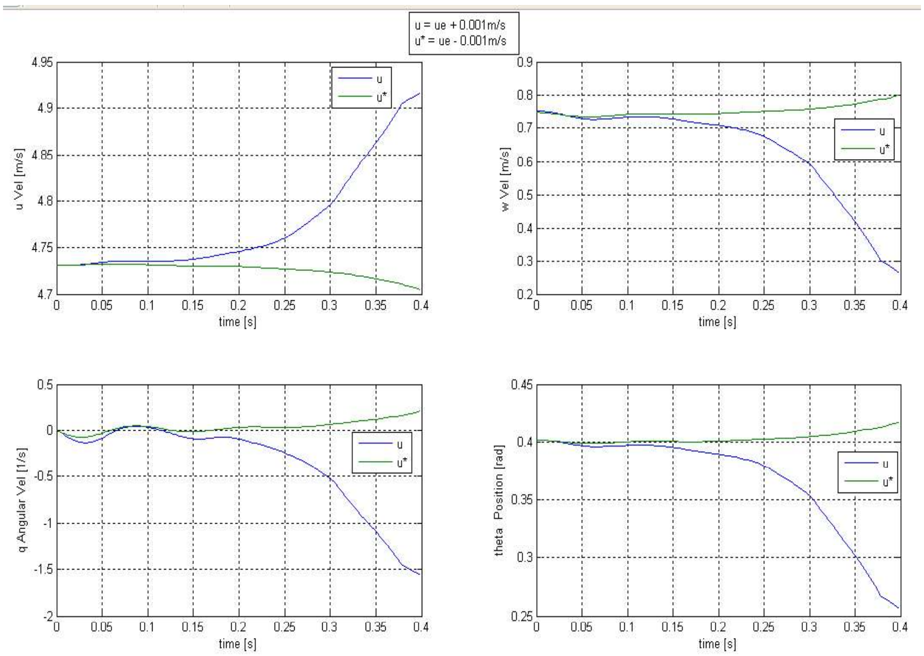


Fig. 3. Simulation for a Non linear time invariant model with perturbation in the u-velocity for locust types "R", "G", and "B", from top to below, respectively.

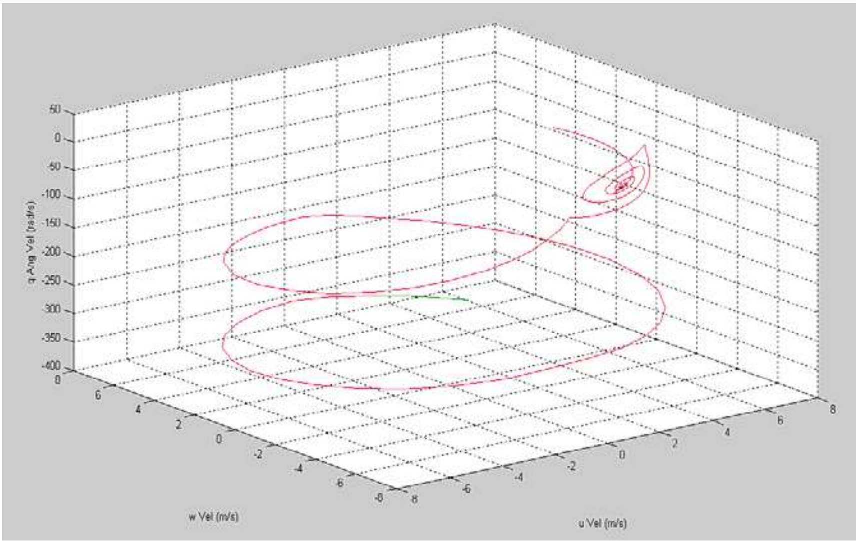


Fig. 4. Phase portrait for θ for the non linear time invariant model for locust type "R".

Finally, it is showed in Fig. 4 the variability of θ with respect to the other three variables (u, w and q). Based on the NLTI model; There are at least two points where

θ changes abruptly when simulation time correspond to 0.6s. These rapid changes in the path of θ implies that once the insect falls in this point then the insect might have change rapidly the path. This situation does not happen in reality, due to instability in the simulation with a set of small spirals which also might be difficult to see in a free flight.

5 Conclusions

This is possible, since several factors were limiting it; for instance, forces were not accurate because of the instruments used, the insect can have different reactions under this "altered conditions" to simulate the flight. Additionally, some assumptions were made as the gravity, weight and moment of inertia are constant which is not true and it is easily noticed in the moment of inertia because of the flapping.

Also, when the experiments were performed, there was a recording of forces in an open loop. Under this situation, it is assumed that the insect does not control the flight, which is not true. Thus forces to manipulate the flight might already be included somehow in the set of data given in the experiment. Additionally, exploring possibilities to control the flight opens the chance to improve methodology to obtain accurate values from experiments and to estimate forces from the set of Newton Euler equations, combined with Extended Kalmann Filters reported by [4].

Even though the model is still weak to show a realistic simulation of an insect flight, methodology to obtain data is strongly improved and computationally algorithms are nowadays very helpful.

References

1. Taylor, G.K., Thomas, A.L.R.: Dynamic flight stability in the desert locust *Schistocerca gregaria*. Journal of Experimental Biology, 206, 2803-2829 (2003)
2. Taylor, G.K., Zbikowski, R.: Nonlinear time-periodic models of the longitudinal flight dynamics of the desert *Schistocerca gregaria*. Journal of the Royal Society Interface 2, 197-221 (2005)
3. Taylor, G.K., Bomphrey, R.J., Hoen, J.: Insect flight dynamics and control. In: Aerospace Science Meeting and Exhibit, Reno Nevada (2006)
4. Garrat, M.: Biologically Inspired Vision and Control for an Autonomous Flying Vehicle. Ph D. Dissertation (2007)