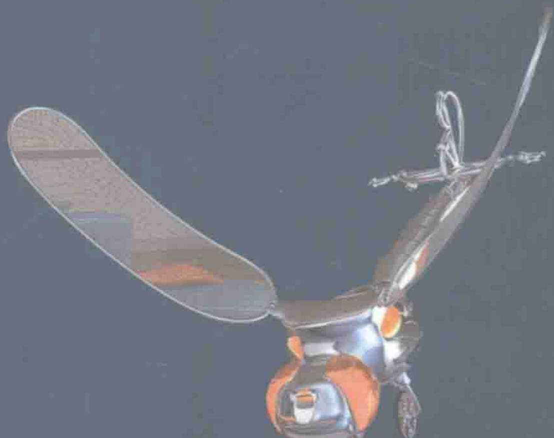
ENGINEERING SCIENCES

Microtechnology

BIO-INSPIRED FLYING ROBOTS

EXPERIMENTAL SYNTHESIS OF AUTONOMOUS INDOOR FLYERS

Jean-Christophe Zufferey



EPFL Press
Distributed by CRC Press

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EPFL Press
A Swiss academic publisher distributed by CRC Press

CRC Press
Taylor & Francis Group

Taylor and Francis Group, LLC
6000 Broken Sound Parkway, NW, Suite 300,
Boca Raton, FL 33487

Distribution and Customer Service
orders@crcpress.com

www.crcpress.com

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

This book is published under the editorial direction of Professor Peter Ryser.

For the work described in this book, Dr. Jean-Christophe Zufferey was awarded the "EPFL Press Distinction", an official prize discerned annually at the Ecole polytechnique fédérale de Lausanne (EPFL) and sponsored by the Presses polytechniques et universitaires romandes. The Distinction is given to the author of a doctoral thesis deemed to have outstanding editorial, instructive and scientific qualities; the award consists of the publication of this present book.

EPFL Press

is an imprint owned by Presses polytechniques et universitaires romandes, a Swiss academic publishing company whose main purpose is to publish the teaching and research works of the Ecole polytechnique fédérale de Lausanne.

Presses polytechniques et universitaires romandes
EPFL – Centre Midi
Post office box 119
CH-1015 Lausanne, Switzerland
E-Mail: ppur@epfl.ch
Phone: 021 / 693 21 30
Fax: 021 / 693 40 27

www.epflpress.org

ISBN 2-940222-19-3 (EPFL Press)
ISBN 978-1-4200-6684-5 (CRC Press)

Printed in the UK

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Dans la certitude de quels ciels,
au coeur de quels frêles espaces,
étreindre les chauds reflets de vivre ?

Frémis,
Matière qui t'éveilles,
scintille plutôt que ne luis,
tremble comme le milieu de la flamme,
Matière qui virevoltes et t'enfuis
et,
parmi les vents illimités de la conscience,
aspires à être…

Julien Zufferey

Preface

Indoor flying robots represent a largely unexplored area of robotics. There are several unmanned aerial vehicles, but these are machines that require precise information on their absolute position and can fly only in open skies far away from any object. Flying within, or among buildings requires completely different types of sensors and control strategies because geo-position information is no longer available in closed and cluttered environments. At the same time, the small space between obstacles calls for extreme miniaturization and imposes stringent constraints on energetic requirements and mechatronic design.

A small number of scientists and engineers have started to look at flying insects as a source of inspiration for the design of indoor flying robots. But where does one start? Should the robot look like an insect? Is it possible to tackle the problem of perception and control separately from the problem of hardware design? What types of sensors should be used? How do insects translate sensory information in motor commands? These and many other questions are clearly addressed in this book as the author progresses towards the solution of the puzzle.

Biological inspiration is a tricky business. The technology, so to speak, used by biological organisms (deformable tissues, muscles, elastic frameworks, pervasive sensory arrays) differs greatly from that of today's robots, which are mostly made of rigid structures, gears and wheels, and comparatively few sensors. Therefore, what seems effective and efficient in biology may turn out to be fragile, difficult to manufacture, and hard to control in a robot. For example, it is still very debated to which extent robots with rigid legged locomotion are better than robots with articulated wheels.

Also, the morphologies, materials, and brains of biological organisms co-evolve to match the environmental challenges at the spatial and temporal scales where those organisms operate. Isolating a specific biological solution and transposing it into a context that does not match the selection criteria for which that solution was evolved may result in sub-optimal solutions. For example, the single-lens camera with small field of view and high resolution that mammalian brains evolved for shape recognition may not be the most efficient solution for a micro-robot whose sole purpose is to rapidly avoid obstacles on its course.

Useful practice of biological inspiration requires a series of careful steps: (a) describing the challenge faced by robots with established engineering design principles; (b) uniquely identifying the biological functionality that is required by the robot; (c) understanding the biological mechanisms responsible for that functionality; (d) extracting the principles of biological design at a level that abstracts from the technological details; (e) translating those principles into technological developments through standard engineering procedures; and (f) objectively assessing the performance of the robot.

Beside the fascinating results described by the author, this book provides an excellent example of biologically inspired robotics because it clearly documents how the steps mentioned above translate practically into specific choices. This book is also a unique documentary on the entire process of conceiving a robot capable of going where no other robot went before. As one reads through the pages, images of the author come to mind devouring books on flying robots and insects; traveling to visit biologists that culture houseflies and honeybees; spending days in the lab putting together the prototypes and implementing the control circuits; and then finally analyzing the flying abilities of his robots just as his fellow biologists do with insects.

Technology and science will continue to progress, and flying robots will become even smaller and more autonomous in the future. But the ideas, pioneering results, and adventure described in this book will continue to make it a fascinating reading for many years to come.

Dario Floreano

Foreword

The work presented in this book is largely derived from my thesis project, funded by the Swiss National Foundation and carried out at the Swiss Federal Institute of Technology in Lausanne (EPFL), in the Laboratory of Intelligent Systems (http://lis.epfl.ch), under the supervision of Prof. Dario Floreano. This has been a great time during which I had the opportunity to conjugate two of my passions: aviation and robotics. As an aerobatic and mountain-landing pilot, I often felt challenged by these small insects that buzz around flawlessly while exploring their highly cluttered environment and suddenly decide to land on an improbable protuberance. We, as humans, need charts, reconnaissance, weather forecasts, navigational aids; whereas they, as insects, just need the wish to fly and land, and can do it with a brain that has one million times fewer neurons than ours. This is at the same time highly frustrating and motivating: frustrating because engineers have been unable to reproduce artificial systems that can display the tenth of the agility of a fly; motivating because it means that if insects can do it with such a low number of neurons, a way must exist of doing it simply and small. This is why I have been compelled towards a better understanding of the internal functioning of flying insects in order to extract principles that can help synthesize autonomous artificial flyers. Of course it has not been possible to reach the level of expertise and agility of an actual fly within these few years of research, but I hope that this book humbly contributes to this endeavor by relating my hands-on experiments and results. Since (moving) images are better than thousands of (static) words, especially when it comes to mobile robotics, I decided to create and maintain a webpage at http://book.zuff.info containing a list of links, software and videos related to artificial, most of the time bio-inspired, flying robots. I hope it will help you feeling the magic atmosphere surrounding the creation of autonomous flyers.

Of course, I did not spend these years of research completely alone. Many colleagues, undergraduate students and friends have contributed to the adventure and I am sorry not being able to name all them here. However, I would like to cite a few, such as Jean-Daniel Nicoud, André Guignard, Cyril Halter and Adam Klaptocz who helped me enormously with the construction of the microflyers; Antoine Beyeler and Claudio Mattiussi with whom I had countless discussions on the scientific aspects; Adam and Antoine, along with Markus Waibel and Céline Ray, also contributed with many constructive comments on the early manuscripts of this text. External advisors and renowned professors, especially Roland Siegwart, Mandyam Srinivasan, and Nicolas Franceschini, have been key motivators in the fields of mobile and bio-inspired robotics. I also would like to express my gratitude to my parents and family for their patience, for nurturing my intellectual interests since the very beginning, and for their ongoing critical insight. Finally, I would like to thank Céline for her love, support, and understanding, and for making everything worthwhile.

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CHAPTER 1

Introduction

Flies are objectionable in many ways, but they now add insult to injury by showing that it is definitely possible to achieve the smartest sensory-motor behavior such as 3D navigation at 500 *body-lengths per second using quite modest processing resources.*

N. Franceschini, 2004

1.1 What's Wrong with Flying Robots?

Current instances of unmanned aerial vehicles (UAV) tend to fly far away from any obstacles, such as ground, trees, and buildings. This is mainly due to aerial platforms featuring such tremendous constraints in terms of manoeuvrability and weight that enabling them to actively avoid collisions in cluttered or confined environments is highly challenging. Very often, researchers and developers use GPS (Global Positioning System) as the main source of sensing information to achieve what is commonly known as "way-point navigation". By carefully choosing the way-points in advance, it is easy to make sure that the resulting path will be free of static obstacles. It is indeed striking to see how research in flying robotics has evolved since the availability of GPS during the mid-1990's[(1)]. GPS enables a flying robot to

(1) After four years of competition, the first autonomous completion of an object retrieval task at the International Aerial Robotics Competition occurred in 1995 and was performed by the Standford team who was the first to use a (differential) GPS.

be aware of its state with respect to a global inertial coordinate system and – in some respects – to be considered as an end-effector of a robotic arm that has a certain workspace in which it can be precisely positioned. Although localisation and obstacle avoidance are two central themes in terrestrial robotics research, they have been somewhat ignored in the aerial robotics community, since it was possible to effortlessly solve the first one by the use of GPS and ignore the second as the sky is far less obstructed than the Earth surface.

However, GPS has several limitations when it comes to low-altitude or indoor flight. The signal sent by the satellites may indeed become too weak, be temporary occluded, or suffer from multiple reflections when reaching the receiver. It is therefore generally admitted that GPS is unreliable when flying in urban canyons, under trees or within buildings. In these situations, the problem of controlling a flying robot becomes very delicate. Some researchers use ground-based beacons or tracking systems to replace the satellites. However, this is not a convenient solution since the use of such equipment is limited to pre-defined environments. Other researchers are attempting to equip flying robots with the same kind of sensors that are commonly found on terrestrial mobile robots, i.e. range finders such as sonars or lasers [Everett, 1995; Siegwart and Nourbakhsh, 2004; Bekey, 2005; Thrun *et al.*, 2005]. The problem with this approach is that not only do flying systems possess a very limited payload, which is very often incompatible with such sensors, but, in addition, they must survey a 3D space whereas terrestrial robots are generally satisfied with 2D scans of their surroundings. Moreover, because of their higher speed, flying robots require longer ranges of sensing, which in turn requires heavier sensors. The only known system that has been able to solve the problem of near obstacle flight using a 3D scanning laser range finder is a 100 kg helicopter equipped with a 3 kg scanning laser range finder [Scherer *et al.*, 2007].

Even if the GPS could provide an accurate signal in near obstacle situations, the localisation information *per se* does not solve the collision avoidance problem. In the absence of continuously updated information concerning the surrounding obstacles, one needs to embed a very accurate 3D map of the environment in order to achieve collision-free path planning. In addition, environments are generally not completely static, and it is very difficult to incorporate into maps changes such as new buildings, cranes, etc. that could significantly disturb a UAV flying at low altitude. Apart from the problem of constructing such a map, this method would require a significant amount of memory and processing power, which may be well beyond the capability of a small flying system.

In summary, the aerial robotics community has been somehow refrained from effectively tackling the collision avoidance problem since GPS has provided an easy way around it. This problem is definitely worth getting back to in order to produce flying robots capable of flying at lower altitude or even within buildings so as to, e.g. help in search and rescue operations, provide low-altitude imagery for surveillance or mapping, measure environmental data, provide wireless communication relays, etc. Since the classical approach used in terrestrial robotics – i.e. using active distance sensors – tends to be too heavy and power consuming for flying platforms, what about turning to living systems like flies? Flies are indeed well capable of solving the problem of navigating within cluttered environments while keeping energy consumption and weight at an incredibly low level.

1.2 Flying Insects Don't Use GPS

Engineers have been able to master amazing technologies in order to fly at very high speed, relatively high in the sky. However, biological systems far outperform today's robots at tasks involving real-time perception in cluttered environments, in particular if we take energy efficiency and size into account. Based on this observation, the present book aims at identifying the biological principles that are amenable to artificial implementation in order to synthesise systems that typically require miniaturisation, energy efficiency, low-power processing and fast sensory-motor mapping.

The notion of a *biological principle* is taken in a broad meaning, ranging from individual biological features like anatomy of perceptive organs, models of information processing or behaviours, to the evolutionary process at the level of the species. The idea of applying biological principles to flying robots draws on the fields of biorobotics[(2)] [Chang and Gaudiano, 2000; Webb and Consi, 2001] and evolutionary robotics [Nolfi and Floreano, 2000]. These philosophical trends have in turn been inspired by the new artificial intelligence (new AI), first advocated by Brooks in the early 1980's (for a review, see Brooks, 1999) and by the seminal contribution from Braitenberg [1984]. However, when taking inspiration from biology in order to engineer artificial systems, care must be taken to avoid the pitfall of carrying out biomimicry for the sake of itself, while forgetting the primary goal, i.e. the realisation of functional autonomous robots. For instance, it would make no sense to replace efficiently engineered systems or subsystems by poorly performing bio-inspired solutions for the sole reason that they are bio-inspired. In our approach, biological inspiration will take place at different levels.

The first level concerns the selection of sensory modalities. Flies do not use GPS, but mainly low-resolution, fast and wide field-of-view (FOV) eyes, gyroscopic sensors and airspeed detectors. Interestingly, these kinds of sensors can be found in very small and low-power packages. Recent developments in MEMS[(3)] technology allow the measurement of strength, pressure, or inertial forces with ultra-light devices weighing only a few milligrams. Therefore, artificial sensors can easily mimic certain proprioceptive senses in flying insects. Concerning the perception of the surroundings, the only passive sensory modality that can provide useful information is vision. Active range finders such as lasers or sonars have significant drawbacks such as their inherent weight (they require an emitter and a receiver), their need to send energy into the environment, and their inability to cover a wide portion of the surroundings unless they are mounted on a mechanically scanning system. Visual sensors, on the other hand, can be extremely small, do not need to send energy into the environment, and have by essence a larger FOV. It is probable that these same considerations have driven evolution toward extensive use of vision in flying insects rather than active range finders to control their flight, avoid collisions and navigate in cluttered environments.

[(2)] Also called bio-inspired robotics or biomimetic robotics.
[(3)] Micro-Electro-Mechanical Systems.