Real-Time Microforce Sensors and High Speed Vision System for Insect Flight Control Analysis

Chauncey F. Graetzel[1,2], Steven N. Fry[2], Felix Beyeler[1], Yu Sun[3], and Bradley J. Nelson[1]

[1] Institute of Robotics and Intelligent Systems
ETH Zurich
8092 Zurich, Switzerland
{cgraetzel, fbey, bnelson}@ethz.ch
http://www.iris.ethz.ch

[2] Institute of Neuroinformatics
ETH/UNI Zurich
8057 Zurich, Switzerland
steven@ini.phys.ethz.ch
http://www.fly.ini.unizh.ch

[3] Advanced Micro and Nanosystems Laboratory
University of Toronto
Toronto, Canada
sun@mie.utoronto.ca
http://amnl.mie.utoronto.ca

Summary. In this paper, we show how "bio-inspired" robotics can benefit from a more generalized approach than case-by-case emulation. This generalization is obtained by investigating the design constraints found in biological organisms using a reverse-engineering approach. To achieve this, we have developed two novel technologies that are well suited to analyze the biomechanics and neural control in insect flight. First, we present a micro-electro-mechanical (MEMS) force sensor for measuring flight forces. Second, we describe a 6000Hz high speed vision system for characterizing wing kinematics in real time. Finally, we integrate these technologies within a tethered flight "simulator" for open and closed-loop investigations of sensory-motor pathways. Initial results are presented and future research perspectives are discussed.

1 Introduction and State-of-Art

1.1 The Need for Generalization in "bio-inspired" Robotics

Robotics and biology have a strong potential to interact and mutually benefit from each other. On the one hand, biology provides engineering with model organisms and a wealth of knowledge concerning nature's mechanisms. On the other hand, robotics provides biology with novel technical tools as well as rigorous reverse-engineering approaches.

The intermediate size scales ranging from the millimeter to the micrometer is a domain particularly interesting for this interdisciplinary research to

O. Khatib, V. Kumar, and D. Rus (Eds.) Experimental Robotics, STAR 39, pp. 451–460, 2008.
springerlink.com

take place. Nature has evolved very successful organisms at these size scales. Evolutionary processes have had millions of years to improve their design. Engineering, however, has only recently started building at these scales with the advent of microelectronics in the past twenty years. In turn, this recent expansion of micro-technologies is providing biological research with new experimental paradigms and has also fostered interest in small scale biological organisms.

Recently, many efforts have concentrated on engineering products by mimicking nature, such as the design of dry adhesives inspired by gecko foot hair [1]. Unfortunately, these efforts have had little practical impact yet. One of the main causes of this struggle is that biological organisms have evolved highly specialized solutions using nature's building blocks. These building blocks differ in very fundamental ways from the ones used by man, therefore making the artificial version suboptimal in design or even impossible to build.

Our approach focuses on the higher level aspects of these systems, where biological and engineered system are still comparable because the generalization level is adequate. The basic common challenge shared by natural and artificial devices are environmental design constraints. It is only by understanding and physically quantifying the limiting factors found in nature that one can learn how to better cope with them in engineering. Beyond this, their paths diverge quickly. In other words, the field of bio-inspired robotics is truly in need of *reverse-engineering* approaches to go beyond case-by-case emulation.

1.2 Our Contributions

In this paper, we present two novel technologies for analyzing insect flight control. We chose the neuromotor flight control system of the well-studied fruit fly *Drosophila melanogaster* as a model system to study sensor motory pathways. The fruit fly is capable of impressive flight maneuvers that depend on extremely rapid and precise wing actuation modulated by reflexive control loops. For these reasons, flies have recently attracted interest for the purpose of developing micro aerial vehicles [2]. Lessons learned from understanding the link between the neurophysiology and biomechanics of their flight behavior may also be of value to other types of autonomous microrobotic systems.

Tethered flight experiments provides a powerful technique for analyzing flight control for several reasons. First, tethered flight allows the use of detailed behavioral metrics such as the MEMS force sensor and high speed computer vision system proposed in this paper (Fig. 1). Second, the environment is controllable and therefore ideal to present precise visual inputs by using specialized displays. Finally, the artificial decoupling of behavior and its subsequent sensory feedback allows novel experimental paradigms to be implemented (Fig. 1).

1.3 Problem Statement and Related Work

One goal of this work is to produce a technology that can measure the flight forces produced by a tethered fruit fly. The fruit fly beats its wings at around 200Hz,

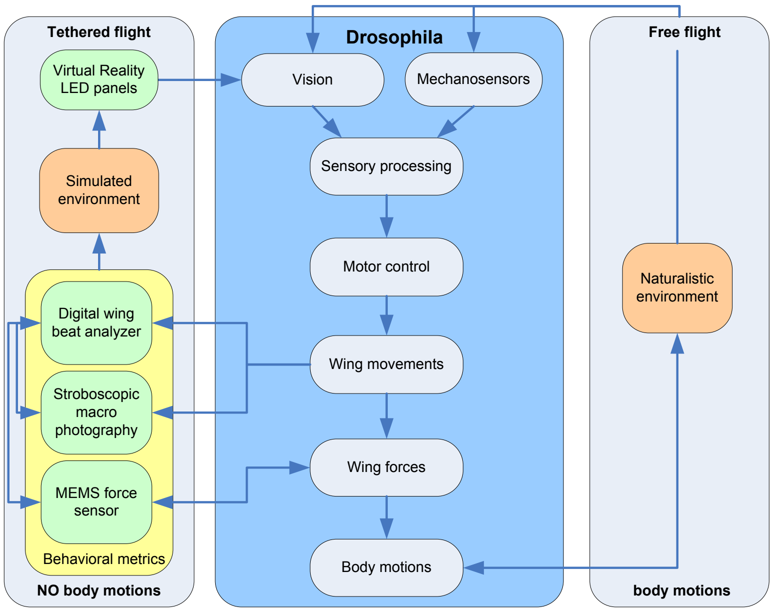

Fig. 1. Overview of the technical tools and their application in the reverse-engineering approach adopted here. The tethered flight paradigm is depicted on the left. The green boxes show the technologies employed in our approach and described in detail in this paper.

generating instantaneous lift forces ranging up to 50μN and containing relevant harmonics up to 3kHz. To measure these forces, a sensor must be able to sample at a sub-micro Newton resolution and a bandwidth above 6kHz. From a practical point of view, the sensor must be easily tethered to the fruit fly in the correct orientation. Previous attempts to directly measure flight forces were limited in terms of bandwidth and resolution [3]. Modern MEMS technology provides new options for practical and compact solutions, which can be extended to multiple degrees of freedom (DOF) [4].

Another goal of this work is to develop a technology to instantaneously measure the wing kinematics. The wings move along complex trajectories whose faithful and complete reconstruction requires a minimum sampling frequency of 2kHz to be reconstructed correctly [5, 6]. Moreover, a high spatial resolution of the wing position is necessary because the variations in wing kinematics are subtle. Previous attempts to characterize wing kinematics in real time resulted in a system based on an optical photodiode which measured relative stroke amplitude [7]. Our new system based on computer vision system has the advantages that it produces a more complete kinematic reconstruction and that it is highly adaptable since it relies on digital technologies.

2 MEMS Force Sensor: Technical Approach and Results

We developed a capacitive MEMS micro force sensor that has a high sensitivity (1.35mV/N), good linearity (<4%) and a large bandwidth (8kHz) [8]. We achieved these characteristics using a configuration of bulk micromachined differential triplate comb drives (Fig. 2). We applied a high-yield fabrication process using deep-reactive ion etching (DRIE) on silicon-on-insulator (SOI) wafer. We used four lithographic masks to construct the high aspect ratio devices. The process features dry release of both suspended structures and the entire device in order to protect fragile components. The sensor's mechanical characteristics are defined by the springs' dimensions, which can be modified on the lithographic mask to achieve various stiffnesses and sensitivities. Based on the same principle, multi DOF force sensors can be built for the combined measurement of flight forces and torques.

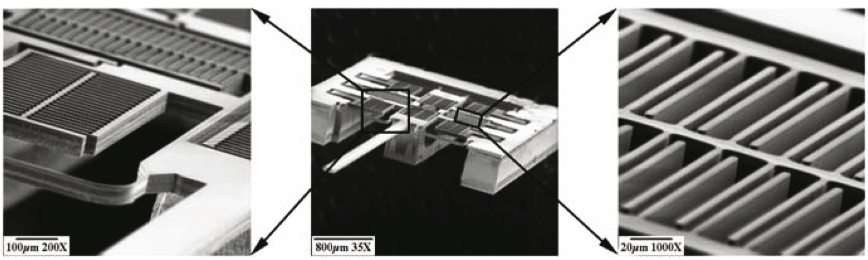

Fig. 2. SEM image of the developed 2 DOF force sensor (center image). The left image provides a detailed view of one of the springs. The right image shows a close-up view of the comb structures.

3 High Speed Vision: Technical Approach and Results

We sample wing positions at 6kHz using a newly developed high speed computer vision system [9]. This high frame rate is reached by using a camera with dynamic regions of interest (ROI) to increase temporal resolution from localized sampling without loss of spatial resolution. The number of transferred pixels is reduced by only exposing the areas around the current wing. To achieve this, the system is initially calibrated during an offline procedure by extracting mean wing paths (Fig. 3).

During real time acquisition, these wing paths are used as a guide to position the search windows. Only the pixels along the wing paths are processed, further reducing the computation time. The tracking is initialized by positioning the search window at one of the path extrema. When the wing passes through the search window, it triggers the wing following (Fig. 4). An extended Kalman filter fits an *a priori* kinematic model to past wing position measurements, allowing the position of the next search window to be computed and providing an analysis of kinematic data in real time. Using this approach, we sampled the wing position

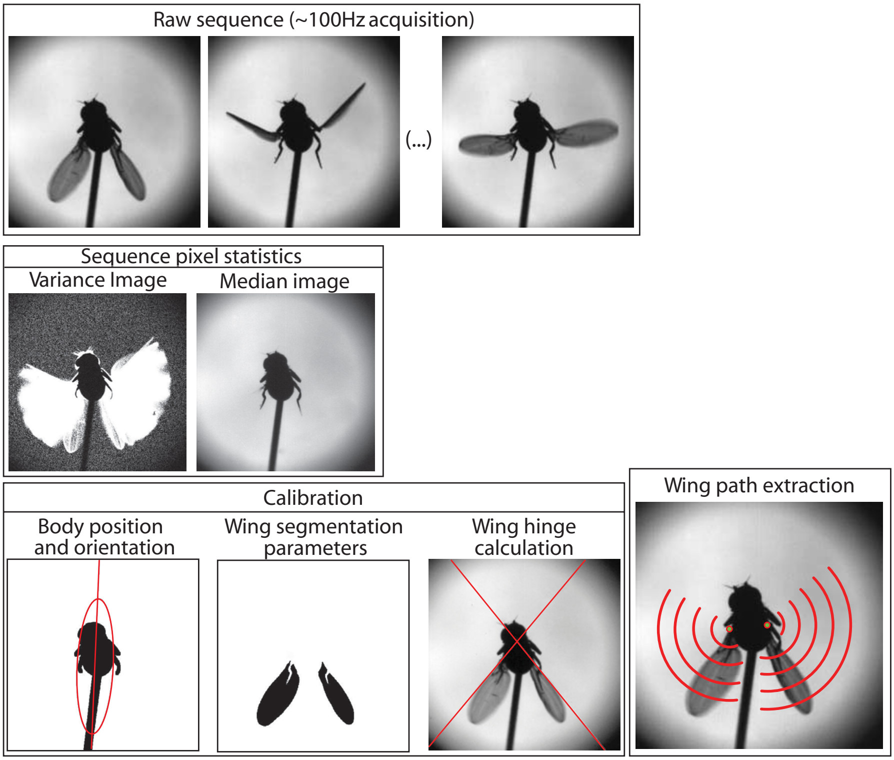

Fig. 3. Calibration procedure. During calibration, a set of fifty full-scale images (top row) is acquired at random wing phases. Each pixel's statistical median and variance throughout the sequence are calculated (middle row). Using standard image processing tools, the position of the body and the wing hinges is calculated. Finally, the wing paths are extracted (bottom right image).

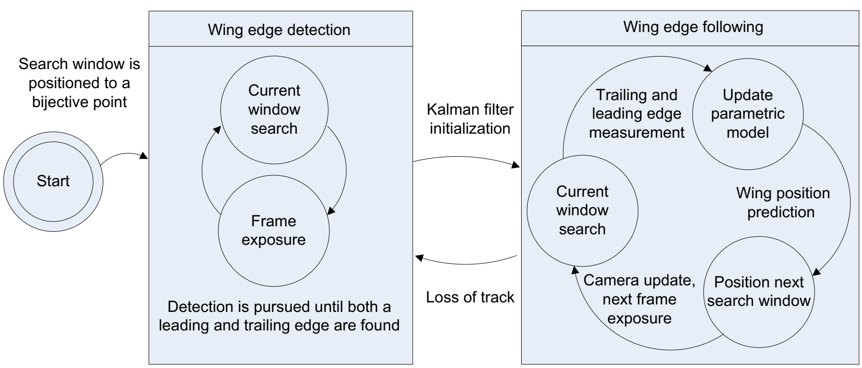

Fig. 4. State machine of the wing beat analyzer. During wing detection (left side), the ROI is kept fixed at one of the extrema of the wing paths until a wing passes through it. During wing following (right side), the position of the next ROI is adapted to follow the wing through its path.

at 6250Hz with a resolution of 1°, using a ROI of approximately 3600 pixels (Fig. 5 and 6) This is more than four times faster than other computer vision based tracking systems reported to date[10, 11].

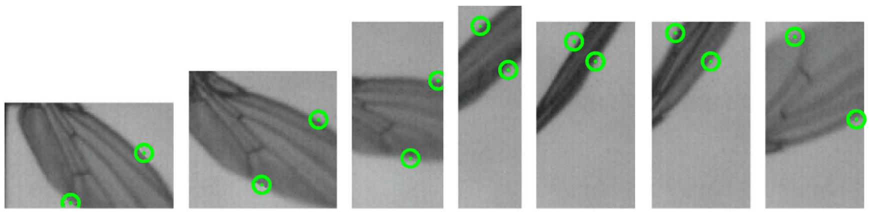

Fig. 5. Typical sample from the tracking sequence. Leading and trailing edges are indicated by circles. The position and size of the ROI is adapted at each time step according to the prediction of the wing position. This reduces the amount of pixels exposed, transferred and processed, thus increasing temporal resolution without loss of spatial resolution.

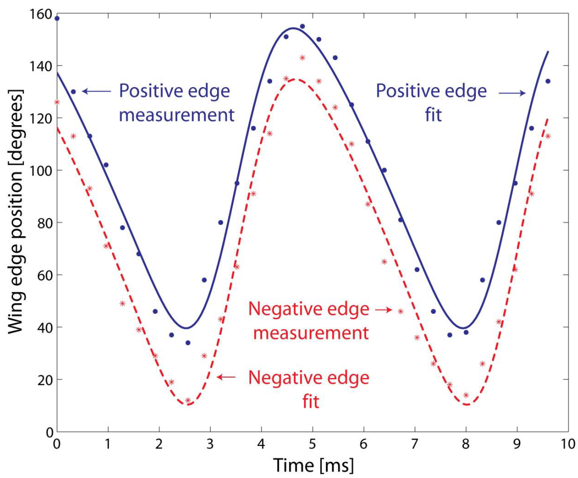

Fig. 6. Tracking results for one wing with the camera running at 6250Hz. The positive and negative edge fit (red and blue lines) correspond to the EKF process state at a given measurement. The kinematics of the positive and negative edge are modeled by a truncated Fourier series with a fixed shape. The spatial offset and amplitude, as well as the temporal phase and frequency, constitute the process state vector. The EKF serves not only to predict the future position of the wing, but also to extract behavioral metrics from the measurements in real time.

4 Experimental Applications

Cold-immobilized fruit flies were glued to the probe of the MEMS force sensor (Fig. 7). After warming, the flies initiated flight. The force sensor with the

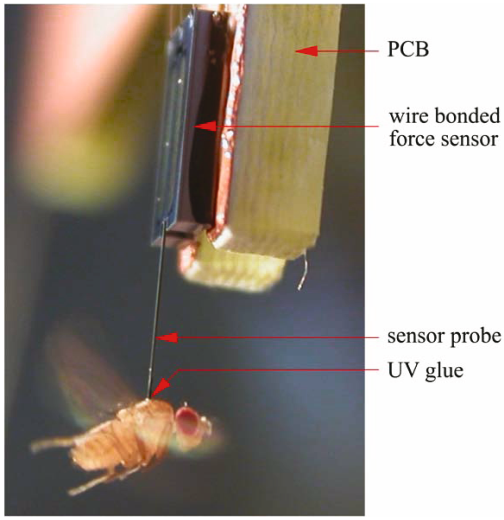

Fig. 7. Close-up picture of the fruit fly tethered to the MEMS force sensor. Cold-immobilized fruit flies were glued to the sensor probe using U.V. curing glue.

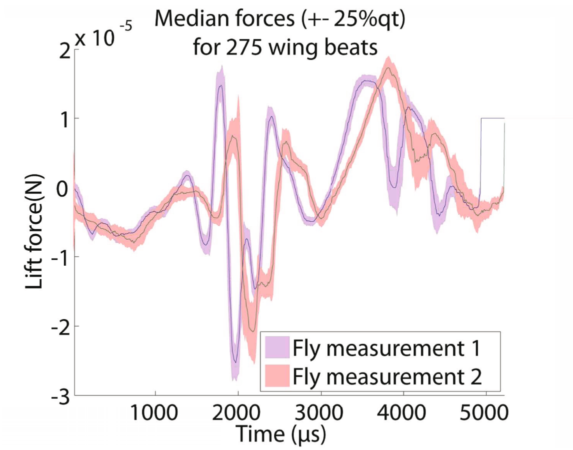

Fig. 8. Typical flight force measurements using the MEMS force sensor for two flies. n1=n2=275 wing beats. Colored areas show 25%-75% percentile range.

attached fly was positioned under the high speed camera, where forces and wing kinematics were measured synchronously (see Fig 9). The wings were backlight with an infrared light source, which is invisible to the fruit fly's visual system [12]. We used custom-built LED screens based on a design from the Dickinson Lab at Caltech [13]. The screens were employed to visually stimulate the flies at update rates of 300Hz (see Fig. 9).

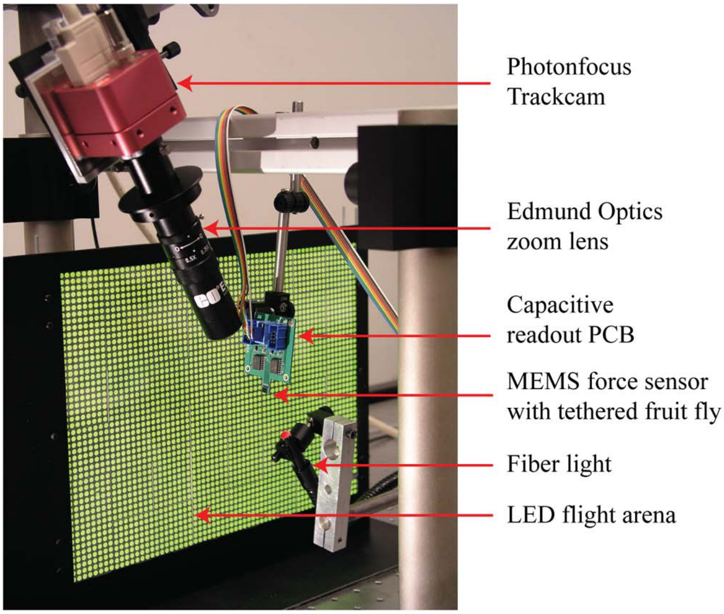

Fig. 9. Experimental setup (one LED screen was removed for better visibility)

This experimental setup is used to address different questions relating to flight control. A typical approach consist of presenting a planned sequence of patterns and measuring the behavioral output synchronously. This open-loop approach is well suited to perform a system's identification analysis of flight since inputs and outputs to the biological black box are known.

In one example of the analysis of flight control, we analyze the lift response by displaying vertically-moving sinusoidal gratings on the LED screens at various velocities and measuring the fly's response. We then fit standard models from classic control theory [14] to the data sets to identify control strategies. The combined measurement of kinematic and dynamic data also provide a means to catalog biomechanical maneuvers linked to low-level flight control.

The real-time capabilities of our read-out systems can be used to control external devices such as strobe lighting. By triggering the strobe on the precise phase that is extracted from the high speed vision system, high-quality photographic reconstructions of the wing and mechanosensory kinematics are performed. These images will allow more detailed analysis of the wing kinematics than before [6].

Another application of the real-time capabilities consists in employing the measured output to control the visual input, effectively closing the control loop. For instance, a pattern can be moved left or right as a function of the yaw torque. This adds an entirely new dimension to the experiments used to verify the control models.

5 Conclusion and Research Perspective

There is a requirement for micro-force measurement and high speed tracking for the analysis of biological micro systems, as well as for micro and nano-robots. Our results show the ability of robotic tools to provide such measurements by achieving the challenging sensitivities and bandwidths that are necessary. Our results also emphasize the potential of real-time read-out systems at these scales, by showing how their application extends the experimental paradigms to closed-loop strategies.

In the application of these technologies, we show how our tools can benefit the field of biology by opening the doors to a system's identification approach. Our tools precisely control the visual inputs and directly measure the behavioral outputs of our biological "black box". In turn, this allows the use of reverse-engineering approaches based on classic control theory.

Finally, we show how our work can contribute to bio-inspired robotics by analyzing a biological organism using robotics tools at a generalization level where nature and man-made systems are truly comparable. The generalized analysis of design constraints in fruit-flies may lead to novel approaches of robotics at similar dynamic scales.

Acknowledgement

We thank the Swiss National Science Foundation for supporting this work through grant #205321-103910.

References

1. Sitti, M., Fearing, R.S.: Synthetic gecko foot-hair micro/nano-structures as dry adhesives. Journal of Adhesion Science and Technology 17(8), 1055–1073 (2003)
2. Wu, W.-C., Schenato, L., Wood, R.J., Fearing, R.S.: Biomimetic sensor suite for flight control of a micromechanical flying insect: design and experimental results. In: ICRA. IEEE International Conference on Robotics and Automation, Taipei, Taiwan, pp. 1146–1151 (2003)
3. Dickinson, M.H., Götz, K.G.: The wake dynamics and flight forces of the fruit fly Drosophila melanogaster. Journal of Experimental Biology 199, 2085–2104 (1996)
4. Sun, Y., Nelson, B.J., Potasek, D.P., Enikov, E.: A bulk microfabricated multi-axis capacitive cellular force sensor using transverse comb drives. Journal of Micromechanics and Microengineering 12, 832–840 (2002)
5. Fry, S.N., Sayaman, R., Dickinson, M.H.: The aerodynamics of hovering flight in Drosophila. Journal of Experimental Biology 208, 2303–2318 (2005)
6. Zanker, J.M.: The wing beat of Drosophila melanogaster I. Kinematics. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 327, 1–18 (1990)
7. Dickinson, M.H., Lehmann, F.-O., Götz, K.G.: The active control of wing rotation by Drosophila. Journal of Experimental Biology 182, 173–189 (1993)

8. Sun, Y., Fry, S.N., Potasek, D.P., Bell, D.J., Nelson, B.J.: Characterizing fruit fly flight behavior using a microforce sensor with a new comb-drive configuration. Journal of Microelectromechanical Systems 14, 4–11 (2005)
9. Graetzel, C.F., Fry, S.N., Nelson, B.J.: A 6000 Hz computer vision system for real-time wing beat analysis of Drosophila. In: BioRob. The First IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 1–6 (2006)
10. Oku, H., Ogawa, N., Ishikawa, M., Hashimoto, K.: Two-dimensional tracking of a motile micro-organism allowing high-resolution observation with various imaging techniques. Review of Scientific Instruments 76 (2005)
11. Wilburn, B., Joshi, N., Vaish, V., Talvala, E.V., Antunez, E., Barth, A., Adams, A., Horowitz, M., Levoy, M.: High performance imaging using large camera arrays. ACM Transactions on Graphics 24, 765–776 (2005)
12. Juusola, M., Hardie, R.C.: Light adaptation in Drosophila photoreceptors: I. Response dynamics and signaling efficiency at 25 degrees C. Journal of General Physiology 117, 3–25 (2001)
13. Reiser, M.B., Dickinson, M.H.: Modular electronics for rapid development of visual stimuli (in prep.)
14. Sane, S.P., Dickinson, M.H.: The aerodynamic effects of wing rotation and a revised quasi- steady model of flapping flight. Journal of Experimental Biology 205, 1087–1096 (2002)