# *Free Flying Micro Platform* and *Papa-TV-Bot*: evolving autonomously hovering mobots

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## Abstract

This paper outlines the possibilities, the evolution, and the basic technical elements of autonomously hovering micro robots. It consists of three parts. The first part presents the application *Papa-TV-Bot*, a free flying automatic video camera. The second part is a schedule for the long-term development of autonomously hovering mobots[1] in 8 phases. The third part describes the basic technologies of the vehicles of Phases 1 through 3.

## 1 Introduction

It is well known that entities heavier than air cannot stand still in the air without the help of propulsion engines. The only machines capable of free hovering are helicopters [45] [2]. Their ability to move freely in 3-dimensional space [28] makes them important not only for transport but also for looking at the world from unusual viewpoints[3]. This is especially interesting for television and video productions. Aerial video- and photography is also conducted through unmanned vehicles, such as remote controlled helicopters (e.g., [3,11,17,44,47]). Although the size of these vessels is only about 3 to 5 feet in diameter, they are too dangerous for indoor use because of their large, exposed rotors. Additionally, most of them use noisy and grimy combustion engines. Due to their underlying mechanical principles, they are fundamentally unstable with highly nonlinear dynamics [28,23,24].

For these reasons, aerial photography using model helicopters is limited to expert pilots in outdoor environments, and cannot be conducted near or over crowds of people. Nevertheless, these camera positions would be interesting for TV productions [33] of entertainment shows like concerts and sports events. Cameras hovering over an open field, taking shots from directly above the audience, could convey thrilling pictures. Another interesting domain for these vehicles would be hazards of all kinds, such as radiated areas, hostage situations, and structurally unstable buildings into which it is too dangerous to send humans.

In the first part of this paper, I present a scenario with a ***Papa-TV-Bot***. The second part is a **schedule** for the long-term development of autonomously hovering mobots in 8 phases, starting with a simple *Free Flying Micro Platform* (FFMP), developed into a *Papa-TV-Bot*, then into a hyper-intelligent zero-gravity mobot with multi-ethical awareness. In the third part, I describe the basic technologies of a vehicle of the first three phases, the ***Free Flying Micro Platform* (FFMP),** in more detail. It is a Micro Air Vehicle (MAV, [58,35]), "a tiny, self-piloted flying machine," neither bird nor plane, but "it's a little of both with some insect and robot characteristics thrown in" [48]. Therefore, compared to today's R/C helicopters [25] it is smaller (diameter less than 10 inches), quieter (electro motors), safer (rotors hidden in the fuselage), and—most important—it can hover *automatically*.

## 2 Scenario *Papa-TV-Bot*

> *How does the world look through the eyes of a humming bird? Imagine a basketball game: You watch the players from an altitude of twenty feet and then—within seconds—see them from three inches above the court floor. Then you follow the player with the ball across the whole court, always exactly one foot above his shoulder. You pass him and climb up quickly to one inch above the basket, right in time for the slam.*

The device that could deliver these unusual camera perspectives is a 5-inch autonomous rotary-wing MAV with a video camera and wireless transmission. Four electric

[1] The expression *mobot* is defined as "small, computer-controlled, autonomous mobile robot" [51].

[2] Except for VTOL [39] and tiltrotor airplanes [52].

[3] Other domains for these vehicles would be hazards of all kinds, such as radiated areas, hostage situations, and structurally unstable buildings, into which it is too dangerous to send human, as well as search & rescue, surveillance, law enforcement, inspection, aerial mapping, and cinematography [3].

ducted fans and an absolute position sensor enable it to hover automatically. After it is switched on, the mobot automatically stabilizes itself in the air, so that it stays where it was put. To move it away from this initial position, one can use simple voice commands such as *up*, *down*, *left*, and *right*, spoken directly towards the vehicle, or through a walkie-talkie-like communication device. It also accepts more complicated verbal mission requests like "*Follow this person at a distance of 8 feet and an altitude of 5 feet*." Because such a video surveillance activity resembles Paparazzi photographers, the appropriate name for this device is *Papa-TV-Bot:* Paparazzi Television Mobot. To reduce the annoying effects of such a "flying spy camera," another set of intuitive voice commands, like *go away*, let it immediately move away from the speaker. Additionally, it must

- *Avoid obstacles.* If a human or non-human object obstructs the MAV during its filming missions, it must try to fly around it (e.g., [18]).
- *Evade capture.* Due to its purpose of approaching objects very closely and flying over crowds of people, it has to evade somebody trying to catch it.
- *Be Safe*. Because a Papa-TV-Bot is supposed to operate above people, it has to have extensive safety mechanisms. In case of failure of engines or electronics, or if the remote emergency kill-switch is pressed, four gas filled airbags are inflated instantaneously and cover most of the surface of the inoperational vessel. Equipped with these protective airbags, it falls back to earth without causing any harm.

## 3 Schedule

In order to reach the sophisticated level of a *Papa-TV-Bot*, I propose to develop and evolve autonomously hovering mobots gradually. For this purpose, I have defined 8 distinctive phases. In each phase, certain features and abilities are added to the characteristics of the previous phases:

- Phase 1: **Free flying micro platform (FFMP)** for studying helicopter control, automatic control systems, and automatic hovering.
- Phase 2: **Flying camera**: for indoor aerial video, and fast and uncomplicated Electronic News Gathering (ENG) tasks.
- Phase 3: **Listening mobot**: direct voice communication with a mobot.
- Phase 4: **Mobot with crude situational awareness** through its sensors, good for more complex ENG tasks. Due to their autonomy, several mobots per cameraman are possible.
- Phase 5: **Mobot that understands complex spoken language and has refined situational awareness**: intelligent autonomous micro video camera with maximum degrees of freedom.
- Phase 6: **Mobot that learns from experience:** the longer it operates, the more efficiently it behaves.
- Phase 7: **Self-repairing mobot,** or mobots being able to repair each other.
- Phase 8: **Truly intelligent and highly responsible mobot.**

Table 1 outlines the main goals, primary motivations, as well as the important domains of each phase.

Table 1. The 8 Phases for developing autonomously hovering mobots.

| | *Main Goal* | *Primary Motivations* | *What it is good for* | *Domains* |
|---|---|---|---|---|
| **1** | Standing still in air with automatic self stabilization | Building a small (< 10 in.) and quiet (< 70 dBA) entity, which is able to stay still in the air, stabilize itself automatically, and move in three-dimensional space. | **Free flying micro platform (FFMP)** for studying helicopter control, automatic control systems, and automatic hovering. | • Mechanical engineering<br>• Electrical engineering<br>• Aerial robotics<br>• Micro Air Vehicles<br>• Micro Modeling, Indoor Flying |
| **2** | Passive vision | Adding a wireless camera for conveying pictures from otherwise impossible camera positions, e.g., close above crowds of people, as well as complex camera movements like fast and seamless camera travels through narrow and obstacle rich areas | **Flying camera**: for indoor aerial video, and fast and uncomplicated Electronic News Gathering (ENG) tasks. | • Aerial video and photography<br>• AV technology<br>• Electronic News Gathering, Video and TV productions |
| **3** | Simple listening capability | Making it respond to simple verbal requests like *Up! Down! Turn left!* and *Zoom in!* | **Listening mobot**: direct voice communication with a mobot. | • Speech recognition |

| | Main Goal | Primary Motivations | What it is good for | Domains |
|---|---|---|---|---|
| **4** | • Active vision<br>• Simple tasks<br>• Simple morality | • Adding sensors to improve its perception of the environment for human and non-human obstacle avoidance, as well as for evasive behavior<br>• Making it able to understand and carry out tasks like *Come here!* and *Leave me alone!*<br>• Implementing simple moral prime directive *Do not harm anybody or anything* | **Mobot with crude situational awareness** through its sensors, good for more complex ENG tasks. Due to its autonomy, several mobots per cameraman are possible. | • Sensing technology |
| **5** | Complex tasks | Adding more vision and natural language understanding to make it behave like an artificial pet; understanding complex verbal requests like *Follow me! Follow this man in a distance of 5 meters! Give me a close up of John!* | **Mobot that understands complex spoken language and has refined situational awareness**: intelligent autonomous micro video camera with maximum degrees of freedom. | • Vision processing<br>• Natural language processing |
| **6** | Adaptation to environment, emergent robotic behavior | Creating an adaptive, behavior-based autonomous mobot, which learns from interaction with the environment about dangerous objects and situations, as well as about its power management and flying behavior. | **Mobot that learns from experience:** the longer it operates, the more efficiently it behaves. | • Artificial life, Adaptive behavior<br>• Genetic Algorithms, Classifier Systems, Genetic Programming |
| **7** | Use of tools | Modifying it so that it can use external physical tools for simple self repair and self reproduction | **Self-repairing mobot,** or mobots being able to repair each other. | • Mechanical engineering |
| **8** | • Intellect<br>• Cross cultural Morality | • Improving the intelligence up to *Artilect* stage (artificial intellect, ultra-intelligent machine) [14,26]<br>• Connecting an *Artificial Multi Ethical Advisor System* (AMEAS, Cross Cultural Ethical Knowledge) to make sure its behavior is always ethically correct [32] | **Truly intelligent and highly responsible mobot** (Note that [14] expects such devices realized within two human generations.) | • Neuro Engineering<br>• Philosophy, ethics; expert systems |

# 4 Basic technologies of vehicles of the Phases 1 through 3

## 4.1 Phase 1

The FFMP of Phase 1 is appropriate for studying helicopter controls, automatic control systems, and automatic hovering. The vessel is supposed to be simple: it mainly consists of 4 micro electric ducted fans and an absolute position sensor.

### 4.1.1 Sensors and controlling

The main goal of a vehicle of Phase 1 is the ability to hover automatically. The problem of automatic hovering has been addressed by many research projects (e.g., [5,7,28,49]). Most of these projects use inertial sensors like accelerometers and gyroscopes [12]. However, "inertial sensor data drift with time, because of the need to integrate rate data to yield position; any small constant error increases without bound after integration" [6]. Additionally, the size of these sensors limits further miniaturization of the vehicles, which is crucial for the unobtrusiveness of a MAV. On the other hand, absolute position sensing has made much progress lately (e.g., [12,55]). Due to the high accuracy, low latency, and small size of these sensors, I think it is possible to build a simple MIMO control system for automatic hovering that no longer depends on the measurement of accelerations, be they translational or rotational. A self-stabilizing system, based only on absolute position sensing, would decrease the complexity of the control system remarkably. The idea is that the *rotational* movements of the longitudinal (roll) and horizontal axis (pitch), which are usually detected by gyroscopes, could also be detected indirectly through the resulting *translational* movements (forward/backward, left/right). If a rotary-wing vehicle tilts forward (rotational movement), it automatically and instantaneously initiates a linear forward movement. On the other hand, if a control system can limit the linear displacement of a flying mobot to a minimum, horizontal and longitudinal angular movements should automatically be under control too. First, it must be determined whether sensing linear displacement indeed is sufficient to keep a MAV in horizontal balance. However, given the relatively small size and low price of commercially available absolute position sensors on a radio[4] or ultrasonic basis (e.g., [13]), such a construction would be an elegant solution to the automatic hovering problem[5]. An additional heading sensor (magnetic compass) might be necessary for controlling the movements around the vertical axis[6]. However, it has to be mentioned that external active beacons, which are used by most absolute position sensors for the trilateration or triangulation process, conflict with the initial idea of complete autonomy of a flying mobot. Therefore, other sensing technologies and controlling concepts (like onboard vision) might be considered for mobots of later phases[7].

### *4.1.2 Propulsion*

I propose the use of micro electric ducted fans [38,57]. They are less efficient than conventional rotors, but the main advantage of ducted fans is that they are hidden in the fuselage. This means that they protect the operator, nearby personnel, and property from the dangers of exposed rotors or propellers, which is particularly important for indoor MAV. As [1] points out, ducted fan design provides a number of additional advantages, such as reduced propeller or fan noise, and elimination of the need for a speed reducing gear box and a tail rotor. Furthermore, electric ducted fans are quieter than combustion engines [29]. An alternative to the ducted fan would be the much more efficient *Jetfan* [20]. However, this technology is not yet available in the requested small size.

### *4.1.3 Batteries and Power Transmission*

Although using electric motors for propulsion leads to a relatively quite MAV, it has a major disadvantage: compared to fossil fuels, batteries have a low energy density. Therefore, the weight of electric R/C helicopters is much higher than the weight of models with combustion engines. This leads to short free flight performance times: commercially available electric model helicopters only fly for 5 to 15 minutes[8] [25]. Since the battery will be the heaviest part of an electric MAV, it is imperative to use the most efficient technology available, such as rechargeable solid-state or thin-film Lithium Ion batteries (Li+). They have the highest energy density among commercially available batteries (83 Wh/kg), more than twice that of Nickel-Cadmium (NiCd, 39 Wh/kg). Other technologies are even more efficient, like Lithium Polymer (LiPoly, 104 Wh/kg) and the non-rechargeable Zinc Air (ZnAir, 130 Wh/kg). However, these have other drawbacks (e.g., low maximum discharge current) [43], or are not yet available [31,53].

Another possibility to consider for earlier phases is tethering the mobot to batteries on the ground with an “umbilical cord.” This would enable virtually unlimited performance times, at the expense of range and flexibility. Wireless Power Transmission [36] would be interesting, but is not an issue yet [9].

## *4.2 Phase 2*

The vehicle developed in Phase 2 is an **FFMP** (Phase 1), but with the additional functionality of a **Flying Camera.** Such a vehicle could be used for indoor aerial video and simple Electronic News Gathering (ENG) tasks for live coverage. There is no video processing required in Phase 2[10]; therefore, the only additional elements are a micro video camera and a wireless video transmitter. Given the limited payload capability of a MAV, the main selection criteria are weight and size. Fortunately, there is a variety of

[4] [12] mention that “according to our conversations with manufacturers, none of the RF systems can be used reliably in indoor environments.” (pp. 65)

[5] Note that GPS is not an option, both because it is not operational indoors and its accuracy is not high enough for our purpose (even with DGPS).

[6] Another possibility would be to use three absolute position sensors instead of one.

[7] “A truly autonomous craft cannot completely rely on external positioning devices such as GPS satellites or ground beacons for stability and guidance. It must sense and interact with its environment. We chose to experiment with on-board vision as the primary sensor for this interaction” [3].

[8] The current world record is 63 minutes [59].

[9] Important research was conducted in the context of a microwave-powered helicopter that would automatically position itself over a microwave beam and use it as references for altitude and position [8,9,10].

[10] Only Phase 4 might use the video image for obstacle avoidance.

Table 2. Micro Video Cameras.

| *type* | *manufacturer* | *size* | *weight* | *chip* | *horizontal resolution* | *pixels* |
|---|---|---|---|---|---|---|
| PC-17YC [41] | Supercircuits | 1.6x1.6x2.0 in | 2.5 oz | CCD 1/3 in color | 450 lines (> S-VHS) | 410,000 |
| MB-750U [34] | Polaris Industries | 1.5x1.5x0.9 in | 0.9 oz | CCD 1/3 in color | 420 lines | 251,900 |
| PC-51 [42] | Supercircuits | 0.6x0.6x1.4 in | 0.3 oz | CMOS 1/3 in b/w | 240 lines (< VHS) | 76,800 |

Table 3. Wireless Video Transmitters.

| *type* | *manufacturer* | *size* | *weight* | *range* | *frequency* | *output* |
|---|---|---|---|---|---|---|
| VidLink 100 [56] | Aegis | 1.1x0.8x0.4 in | N/A | 500–2500 feet | 434 MHz | 100 mW |
| MP-2 [37] | Supercircuits | 2.0x1.3x0.2 in | 0.5 oz | 700–2500 feet | 434 MHz | 200 mW |
| VID1 [54] | Spymaster | 0.6x0.9 in | N/A | 1000–2000 feet | 434 or 900 MHz | 80–250 mW |

commercially available devices which could meet these criteria. Table 2 lists three possible cameras, Table 3 three transmitters.

### *4.2 Phase 3*

The vehicle developed in Phase 3 is an **FFMP** (Phase 1) with **Flying Camera** functionality (Phase 2), but additionally a **Listening Mobot**, with which direct voice communication in 3D space is possible. The main motivation is to communicate with an autonomous mobot in natural language [50,46]. Natural language access to autonomous mobots has been studied in detail in the context of land-based robots [30], but not for hovering mobots. Because such a vehicle is supposed to stabilize itself automatically, the movements of the platform should *only* be controlled by high level spoken commands such as *go up* and *turn left.* These commands describe only *relative* movements. The actual control of the speed of the fans should be performed automatically by the MIMO system. I suggest 4 categories of speech commands in Phase 3:

- *linear movements*: up, down, left, right, forward, backward
- *turning*: turn left, turn right
- *amount*: slower, faster, stop
- *camera related*: zoom in, zoom out[11]

Michio Sugeno of the Tokyo University of Technology has built a helicopter [49,21,22,23,24] that is eventually supposed to accept 256 verbal commands, such as *fly forward, hover, fly faster, stop the mission and return*. “Tele-control is to be achieved using fuzzy control theory. Ultimately, our helicopter will incorporate voice-activated commands using natural language as 'Fly forward a little bit.' The idea is that a relatively inexperienced remote operator can use natural language voice commands rather than a couple of joysticks that may require months of training. These commands are naturally 'fuzzy' and hence fit into the fuzzy logic framework nicely” [49]. Although the controlling concept is interesting, this helicopter cannot operate indoors; with its overall body length of 3.57m, it is far away from the size requirements of a MAV of Phase 3.

For the same reasons, I suggest using outboard processing of language in Phase 3. Verbal commands are spoken into a microphone that is connected to a standard speech recognition system (e.g., [2,19]). The output is fed into the MIMO system.

## 5 Summary

This paper outlines the possibilities, the evolution, and the basic technical elements of autonomously hovering micro robots.

First, the paper describes the application ***Papa-TV-Bot***: an autonomously hovering mobot with a wireless video camera. This vessel carries out requests for aerial photography missions. It can operate indoors and in obstacle rich areas, where it avoids obstacles automatically. This rotary-wing micro air vehicle (MAV) follows high level spoken commands, like *follow me*, and tries to evade capture.

In part two of the paper, a **schedule** for evolving a simple *Flying Micro Platform* (FFMP) to a Papa-TV-Bot is shown. In even later phases of the schedule, the mobot is supposed to understand complex spoken language such as “*Give me a close up of John Doe from an altitude of 3 feet"* and has refined situational awareness. Furthermore, it learns from experience, repairs itself, and is truly intelligent and highly responsible.

In the last part, a description of the basic technical elements of an FFMP is given; sensors, propulsion, and batteries are discussed in detail. A simple absolute position sensor and four micro ducted fans are the main components of an FFMP of Phase 1. A micro video camera and a wireless transmitter are added in Phase 2. Speech recognition for high level control of the vessel is implemented in Phase 3.

[11] [16] even use speech recognition to tilt the camera of their commercial aerial photography HiCam helicopter.

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## References

1. *Aerobot* [WWW Document]. URL http://www.moller.com/~mi/aerobot.htm (visited 1998, May 6).
2. *AT&T Watson Speech Recognition* (1996, My 31) [WWW Document]. URL http://www.speech.cs.cmu.edu/comp.speech/Section6/Recognition/att.html (visited 1998, May 9).
3. *Autonomous Helicopter Project: Goal Mission Applications: Cinematography* [WWW Document]. URL http://www.cs.cmu.edu/afs/cs/project/chopper/www/goals.html#movies (visited 1998, May 9).
4. *Autonomous Helicopter Project: Vision-based Stability and Position Control* [WWW Document]. URL http://www.cs.cmu.edu/afs/cs/project/chopper/www/capability.html (visited 1998, May 9).
5. Baumann, U. (1998). *Fliegende Plattform*. Unpublished Master's thesis, Institut für Automatik, ETH Zürich, Zürich, Switzerland.
6. Borenstein, J., Everett, H.R., Feng, L., & Wehe, D. (1996). Mobile Robot Positioning – Sensors and Techniques. Invited paper for the *Journal of Robotic Systems*, Special Issue on Mobile Robots. Submitted April 1996, conditionally accepted Aug. 1996. Available FTP: ftp://ftp.eecs.umich.edu/people/johannb/paper64.pdf.
7. Borenstein, J. (1992). *The HoverBot – An Electrically Powered Flying Robot*. Unpublished white paper, University of Michigan, Ann Arbor, MI. Available FTP: ftp://ftp.eecs.umich.edu/people/johannb/paper99.pdf.
8. Brown, W.C. (1997). The Early History of Wireless Power Transmission. *Proceedings of the Space Studies Institute on Space Manufacturing*, Princeton, NJ, May 8-11, 1997. URL http://engineer.tamu.edu/TEES/CSP/wireless/newhist2.htm (visited 1998, May 7).
9. Brown, W.C., Mims, J.R., & Heenan, M.I. (1965). An Experimental Microwave Powered Helicopter. *1965 IEEE International Record*, Vol. 13, Part 5, pp. 225-235.
10. Brown, W.C. (1968). *Experimental System for Automatically positioning a Microwave Supported Platform*. Tech. Rept. RADC-TR-68-273, Contract AF 30(602) 4310, Oct. 1968.
11. *CamCopter Systems* [WWW Document]. URL http://www.camcopter.com/rchelicopter/actioncam.html (visited 1998, May 6).
12. Feng, L., Borenstein, J., & Everett, B. (1994). *Where am I? Sensors and Methods for Autonomous Mobile Robot Localization.* Technical Report, The University of Michigan UM-MEAM-94-21, December 1994. Available FTP: ftp://ftp.eecs.umich.edu/people/johannb/pos96rep.pdf.
13. *FreeD – The wireless joystick* [WWW Document]. URL http://www.pegatech.com/prod.html (visited 1998, May 7).
14. de Garis, H. (1990). The 21st. Century Artilect: Moral Dilemmas Concerning the Ultra Intelligent Machine. *Revue Internationale de Philosophie*, 1990.
15. *Gyrosaucer II E-570* [WWW Document]. URL http://ns.idanet.co.jp/keyence/english/corporate/hobby/saucer.html (visited 1998, May 4).
16. HiCam helicopter [WWW Document]. URL http://bulk.microtech.com.au/hicam/heli.html (visited 1998, May 9).
17. Holbrook, J. (1996). *RC Helicopters – The Collective RPV Page* [WWW Document]. URL http://www.primenet.com/~azfai/rpv.htm (visited 1998, May 6).
18. Holt, B., Borenstein, J., Koren, Y., & Wehe, D.K. (1996). OmniNav: Obstacle Avoidance for Large, Non-circular, Omnidirectional Mobile Robots. *Robotics and Manufacturing* Vol. 6 (ISRAM 1996 Conference), Montpellier, France, May 27-30,1996, pp. 311-317. Available FTP: ftp://ftp.eecs.umich.edu/people/johannb/paper61.pdf.
19. *IBM ViaVoice Gold* (1998, Apr 1) [WWW Document]. URL http://www.software.ibm.com/is/voicetype/us_vvg.html (visited 1998, May 9).
20. *Jetfan – Technology of the Future* (1997, March 29) [WWW Document]. URL http://www.ozemail.com.au/~jetfan/ (visited 1998, May 6).
21. Kahaner, D.K. (1994, Jan 28). *Demonstration of unmanned helicopter with fuzzy control (Report of the Asian Technology Information Program ATIP)* [WWW Document]. URL http://www.atip.or.jp/public/atip.reports.94/sugeno.94.html (visited 1998, May 9).

22. Kahaner, D.K. (1991, Aug 5). *Fuzzy Helicopter Flight Control (Report of the Asian Technology Information Program ATIP)* [WWW Document]. URL http://www.atip.or.jp/public/atip.reports.91/helicopt.html (visited 1998, May 9).
23. Kahaner, D.K. (1993, Apr 12). *Fuzzy Helicopter Control (Report of the Asian Technology Information Program ATIP)* [WWW Document]. URL http://www.atip.org/public/atip.reports.93/copt-fuz.93.html (visited 1998, May 9).
24. Kahaner, D.K. (1995, Mar 20). *Update of fuzzy helicopter research (Report of the Asian Technology Information Program ATIP)* [WWW Document]. URL http://atip.or.jp/public/atip.reports.95/atip95.13.html (visited 1998, May 9).
25. Kataoka, K. (1998, April 27). *A History of Commercial based Electric R/C Helicopters* [WWW Document]. URL http://agusta.ms.u-tokyo.ac.jp/agusta/history.html (visited 1998, May 6).
26. Kelly, P. (1998, Feb 18). *Swiss scientists warn of robot Armageddon.* CNN interactive [WWW Document]. URL http://cnn.com/TECH/science/9802/18/swiss.robot/index.html (visited 1998, May 6).
27. Kobayashi, H. (1998, May 1). *Autonomous Indoor Flying Robot Honey: For communication and/or interaction between semiautonomous agents* [WWW Document]. URL http://www.ifi.unizh.ch/groups/ailab/people/hiroshi/honey.html (visited 1998, May 6).
28. Koo, T-K. J., Sinopoli1, B., Mostov, K., & Hoffmann, F. *Design of Flight Mode Management on Model Helicopters* [WWW Document]. URL http://robotics.eecs.berkeley.edu/~koo/ILP98/koo.4.html (visited 1998, May 7).
29. Lagerstedt, M. (1997, Aug 23). *Ducted Fan Models* [WWW Document]. URL http://loke.as.arizona.edu/~ckulesa/plane_types.html (visited 1998, May 6).
30. Längle, T., Lüth, T.C., Stopp, E., Herzog, G., & Kamstrup, G. (1995). KANTRA – A Natural Language Interface for Intelligent Robots. In U. Rembold, R. Dillman, L. O. Hertzberger, & T. Kanade (eds.), *Intelligent Autonomous Systems* (IAS 4), pp. 357-364. Amsterdam: IOS. Available FTP: ftp://ftp.cs.uni-sb.de/pub/papers/SFB314/b114.ps.gz.
31. Linden, D. (Ed.) (1995). *Handbook of Batteries*. New York, NY: McGraw-Hill, Inc.
32. Marti, S.J.W. (1998, Apr 22). *Artificial Multi Ethical Advisor System (AMEAS)* [WWW Document]. URL http://www.media.mit.edu/~stefanm/FFMP/FFMP_Details.html#AMEAS.html (visited 1998, May 6).
33. *Massachusetts Film Office: Equipment/Vehicle Rental: Airplane & Helicopter Rentals* [WWW Document]. URL http://www.magnet.state.ma.us/film/pg-evr.htm (visited 1998, May 6).
34. *MB-750U* [WWW Document]. URL http://www.polarisusa.com/mb750u.htm (visited 1998, May 9).
35. McMichael, J.M., & Francis, M.S. (1997, August 7). *Micro Air Vehicles – Toward a New Dimension in Flight Experiment* [WWW Document]. URL http://www.darpa.mil/tto/mav/mav_auvsi.htm (visited 1998, May 7).
36. McSpadden, J.O. (1997, June 19). *Wireless Power Transmission Demonstration* [WWW Document]. URL http://www.csr.utexas.edu/tsgc/power/general/wpt.html (visited 1998, May 7).
37. *Microplate Video Transmitter* (1997-1998) [WWW Document]. URL http://www.scx.com/page1.html (visited 1998, May 9).
38. Murray, R. (1996, Jul 11). *The Caltech Ducted Fan: A Thrust-Vectored Flight Control Experiment* [WWW Document]. URL http://avalon.caltech.edu/~dfan/ (visited 1998, May 6).
39. Newsom, W. A. Jr. (1958 Jan). Experimental investigation of the lateral trim of a wing-propeller combination at angles of attack up to 90 degrees with all propellers turning in the same direction. *NACA* TN 4190, pp. 30.
40. Paradiso, J. A. (1996). The interactive balloon: Sensing, actuation, and behavior in a common object. *IBM Systems Journal 35*, Nos 3&4, 473-498.
41. *PC-17YC color microvideo camera* [WWW Document]. URL http://www.scx.com/page7.html (visited 1998, May 9).
42. *PC-51 series inline microvideo camera* [WWW Document]. URL http://www.scx.com/page11.html (visited 1998, May 9).
43. *Rechargeable Systems: Competitive System Matrix* [WWW Document]. URL http://cccsrv.trevano.ch/~blutz/Electronics/ElecAkkus.html (visited 1998, May 7).
44. *Remote Control Aerial Photography* [WWW Document]. URL http://www.flying-cam.com/ (visited 1998, May 6).
45. Sadler, G. (1995, June). *How the helicopter flies* [WWW Document]. URL http://www.copters.com/hist/history_2.html (visited 1998, May 6).
46. Schmandt, C. (1994). *Voice Communication with Computers. Conversational Systems*. New York, NY: Van Nostrand Reinhold.
47. Shelton, R. (1998). *R/C Aerial Photography* [WWW Document]. URL http://www.vision.net.au/~rjs/aerial.html (visited 1998, May 6).

48. Stone, A. (1998, Feb 24). *Flying into the Future: Miniature flying machines could help with warfare, agriculture and more* [WWW Document]. URL http://www.gtri.gatech.edu/rh-spr97/microfly.htm (visited 1998, May 6).
49. Sugeno, M. et al. (1995). Intelligent Control of an Unmanned Helicopter Based on Fuzzy Logic, *Proc. of American Helicopter Society*, 51st. annual Forum, Texas, May 1995.
50. Suereth, R. (1997). *Developing Natural Language Interfaces: Processing Human Conversations*. New York, NY: McGraw-Hill, Inc.
51. Taylor, C., & Jefferson, D. (1995). Artificial Life as a Tool for Biological Inquiry. In C.G. Langton (Ed.), *Artificial Life – An Overview* (pp. 1-13). Cambridge, MA: The MIT press.
52. The Boeing Company (1996-1998). *The Tiltrotor Story* [WWW Document]. URL http://www.boeing.com/rotorcraft/military/v22/1687-main.html (visited 1998, May 6).
53. *Trends in Battery Industry – Shaping Batteries in the Year 2001* [WWW Document]. URL http://spectra.crane.navy.mil/ctinet/battery/trend.htm (visited 1998, May 7).
54. *Vid1 video transmitter* [WWW Document]. URL http://shop.aeinc.com/bgi/hot.html (visited 1998, May 9).
55. Verplaetse, C. (1996). Inertial proprioceptive devices: Self-motion-sensing toys and tools. *IBM Systems Journal 35*, Nos. 3&4, 639-650.
56. *VidLink 100* [WWW Document]. URL http://www.lynx.bc.ca/virtualspy/vidlink.htm (visited 1998, May 9).
57. Wagoner, R. (1998, Mar). *Electric Ducted Fans* [WWW Document]. URL http://www.ezonemag.com/articles/1998/mar/edf/rwag0398.htm (visited 1998, May 6).
58. *What are Micro Aerial Vehicles?* (1998, March 24) [WWW Document]. URL http://www.aero.ufl.edu/~issmo/mav/info.htm (visited 1998, May 7).
59. *World record with an electric helicopter* [WWW Document]. URL http://www.ikarus-modellbau.de/eecowr.htm.