How to Talk to a Papa-TV-Bot:
Interfaces for Autonomously Levitating Robots

Stefan Marti
The Media Laboratory
Massachusetts Institute of Technology
20 Ames Street, Cambridge, MA USA 02139
stefanm@media.mit.edu

Abstract

Developing new ways of thinking about speech for interaction with computers was always part of the agenda of the MIT Media Lab Speech Interface Group [52]. However, I think that soon there will emerge a closely related new area: speech for interaction with mobile entities. By working with Artificial Life and Robotics people at MIT, I have come to the conclusion that speech might be the most appropriate way of human-machine interaction if the machine is a small, autonomous, and mobile entity.

Exploring the paradigms and principles behind these kinds of dialog systems is one thing, applying them to real objects is another. Unfortunately, small ultra-mobile autonomous entities to test the appropriateness of speech interaction are not available yet. However, I would be highly motivated to try to build a prototype, in interaction with Media Lab and MIT people, if I would be given the necessary means. I am convinced that the Speech Interface Group has a lot of relevant knowledge to solve the upcoming human-machine interface problems.

In the following, I will describe the possibilities, the evolution, and the basic technical elements of autonomously hovering micro robots, the perfect test bed for exploring the above mentioned paradigms. There are three main sections. First, the application *Papa-TV-Bot*, a free flying automatic video camera; second, a schedule for the long-term development of autonomously hovering mobots[1] in 8 phases; and third, the basic technologies of the vehicles of Phases 1 through 3 as well as 8.

1 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. Electric ducted fans and an absolute

[1] Mobot = small, computer-controlled, autonomous mobile robot [59].

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., [21]).
- *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.

2 Executive summary

What is my area of research?

My area of research is how humans would communicate with compact, levitating, autonomous robots. What should be the interface to such a small, ultra mobile, hovering, intelligent machine? How do we design and evaluate such interfaces?

Why is this area important to individuals and society?

These entities do not exist yet, but they certainly will in 20 years. They could be useful for television newsgathering, cinematography, aerial mapping, search and rescue, inspection, and hazards of all kinds such as radiated areas and structurally unstable buildings, into which it is too dangerous to send humans. However, whether these robots prove to be successful depends largely on the design of their human-machine interface.

Intellectual antecedents and important prior work

There are no working ultra mobile, man-made entities yet. However, several researchers are already developing prototypes: some of them use downscaled helicopters [30] (*Figure 1*), some of them imitate small birds and insects [37] (*Figure 2*), and some of them try to apply novel levitation methods like diamagnetism [61,43] (*Figure 3*). The researchers spend most of their time on developing the levitation technology. Therefore, the design of the human-machine interface is still at its embryonic stage. Speech interfaces to mobile entities exist, but the only researcher I am aware of that applied it to free hovering devices tried to control an unmanned helicopter with fuzzy logic speech input [25]. However, researchers have worked on theories of communication that could be relevant. E.g., since such machines can move freely in three-dimensional space, they obviously do not inhabit the same world as we humans do. Therefore, they will not share the same semantics with us [50]. This issue can be important in the design of the human-machine interface. Other work that could be applied to interface design was done in the telerobotics and telepresence domain [e.g., 42]

Research opportunities I want to exploit.

I am building prototypes of ultra-mobile entities, and will test several interface options. I hypothesize that it is not effective to apply conventional machine interfaces like joysticks or buttons to ultra mobile robots. I want to build an interface that enables human to interact with these levitating machines in the most natural way. One of the options that could be useful is natural language; another one is multimodal natural dialog in the sense of Richard Bolt (MIT). Others may come up during the research. In any ways, communication will be on a higher level than just controlling the vessel like a conventional helicopter pilot. The design of the interface has to be scalable: I plan to gradually increase the level of abstraction of the commands, so that eventually, commands are possible like, "Who is on the third floor?" The vessel will find its way there autonomously. It is even possible that mobot would call the help of other devices that are closer to the area of interest or have more appropriate sensors, and can combine their results with information obtained from web searches and other databases.

Impact on individuals and society.

I hope to introduce a new thinking about how to interact with mobile entities that move freely in three-dimensional space. I want to make the research community and the public sensitive to the possible ethical implications of such devices, even before the machines are wide spread. Furthermore, I hope that building prototypes will eventually facilitate daily applications based on such levitating, autonomous mobots. In general, research addressing the problem of effective, natural, and intuitive communication with these machines will make the lives of our children easier. Although these machines are not available yet, it is not too early to tackle the interface problem.

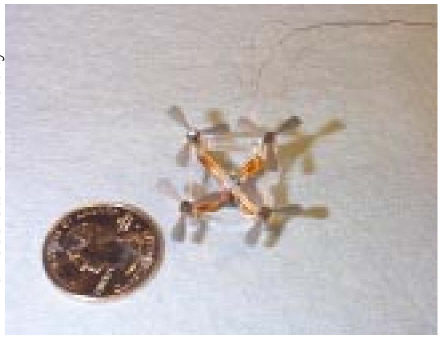

Figure 1: Mesicopter by Ilan Kroo and Fritz Prinz of Stanford University

Figure 2: Entomopter by Robert Michelson of Georgia Tech Research Institute (GTRI)

Figure 3: The flying frog (alive!) at the Nijmegen-Amsterdam Magnet Laboratory

3 Prologue: months, years, and decades

This paper covers planned scientific research activities over the next **four years**. However, it is about more than just that.

- On one side, it is based on a very intense vision of mine that goes very far into the future, probably more than **one hundred years** from now. This part is probably closer to science fiction than to science. (Phase 8 in my Schedule)
- On the other hand, the paper describes the very first, very small steps towards this vision, steps that I can take within the next **few months**. This part is more about aerial robotics than about user interfaces. (Phase 1 in my Schedule)

In this paper, I will write about events that are located far from each other on the time line. Furthermore, some of them are in domains that are not obviously related, e.g., *slow flying* and *ethics*. Although this paper might look heterogeneous, it is all part of the same idea. Some sections zoom in on details, others describe the big picture behind it. See *Figure 4: Onion ring illustration of the eight phases* for an illustration of the different zoom levels, or phases. A detailed description of these phases will follow in the Schedule section (see also *Table 1: The 8 Phases for developing autonomously hovering mobots.)*

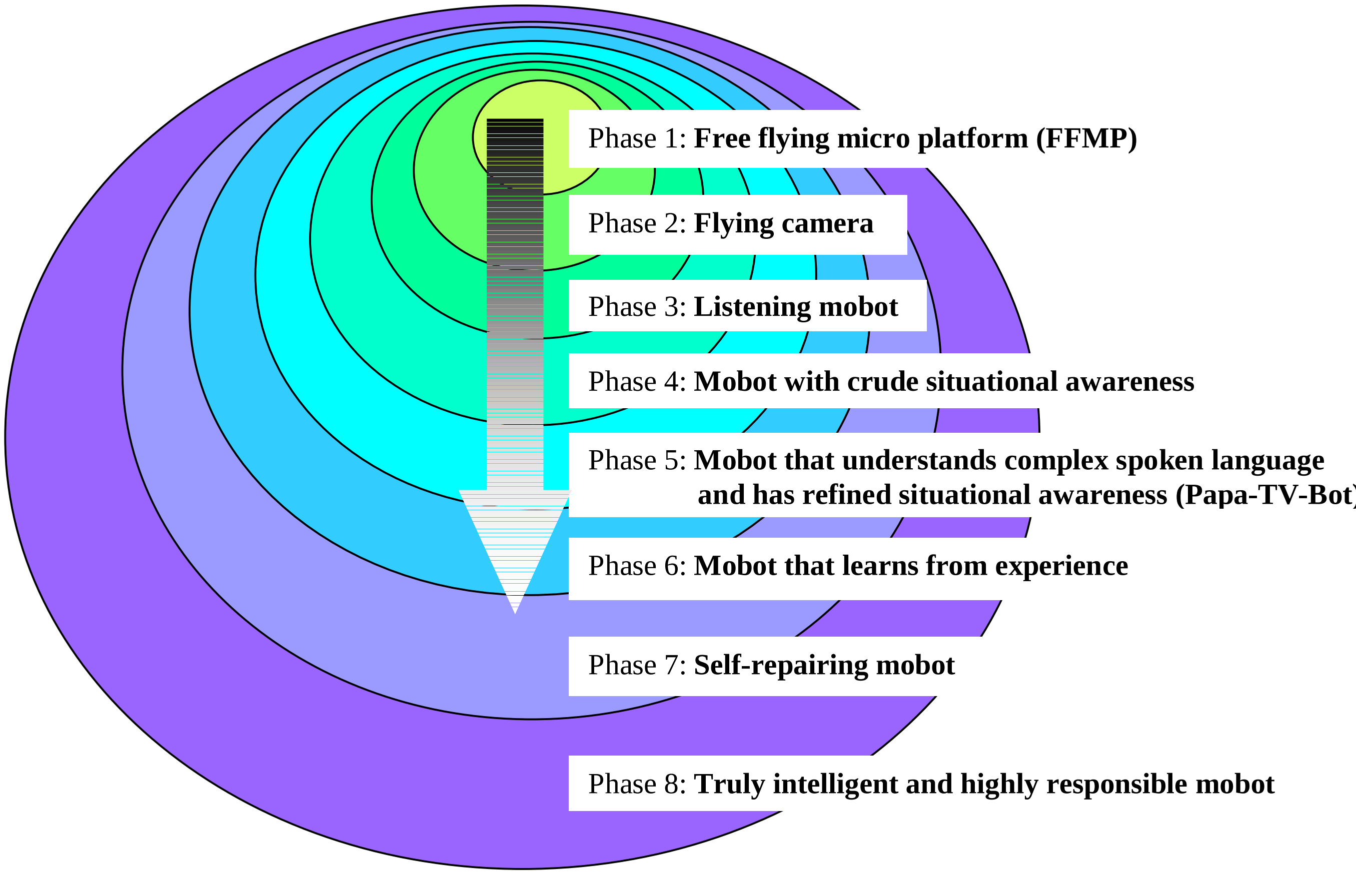

Figure 4: Onion ring illustration of the eight phases

4 Prerequisites: Levitation and small helicopters

Humans are fascinated by levitation. The reason is probably that the world we are living in is three-dimensional. However, human beings live and move mainly in two dimensions. Although they try to exploit the area above and underneath earth level by building structures like houses with several floors, they still live on flat areas within these artifacts.

Additionally, humans seem to have a strong drive to overcome their biological limits. This means, they build machines that enable them to move in three-dimensional space, e.g., airplanes. Humans also try to build machines that are like they are: intelligent, communicative, and mobile—or even *more* mobile than they are. These machines are not restricted to living in two dimensions. Compared to humans, who are biologically built for two dimensions, technological entities do not necessarily have these restrictions.

Still, human-made entities that levitate are rare, especially if no movement is involved, like in hovering. Leaving Science Fiction aside, physics gives several options to levitate things.

- *Lighter than air*. Since air is already light, big volumes of gas are necessary to generate usable lift. This method of levitation is very old. However, there are interesting ideas to revive it, e.g., microscopic diamond spheres that contain a vacuum. Many of these spheres glued together could form a stable material lighter than air.

- *Air flow*. That is the approach most often used today. A helicopter can be considered as a levitation device that uses a stream of air to keep floating. It usually requires a powerful and loud engine to drive a rotor or propeller that accelerates the air.
- *Magnetic levitation*. There are ways to levitate things without any noise or the need for fuel, by using electromagnetic fields. A levitating train is one example. However, a source of energy is always required to keep an object afloat. Removing the battery stops the levitation inevitably. Today's science knows only one way to achieve *real* levitation, i.e. such that no energy input is required and the levitation can last forever. The real levitation makes use of diamagnetism, an intrinsic property of many materials referring to their ability to expel a portion, even if a small one, of an external magnetic field. Electrons in such materials rearrange their orbits slightly so that they expel the external field. As a result, diamagnetic materials repel and are repelled by strong magnetic fields. [61]

There are other options, e.g., rocket engines. However, the method used most often today is airflow, like in helicopters [51] [2].

The ability of helicopters to move freely in 3-dimensional space [29] makes them important not only for transport, but also for looking at the world from unusual viewpoints. This is especially interesting for television and video productions. Aerial video- and photography is also conducted through unmanned vehicles, such as remote controlled helicopters [6,12,20,1]. 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 [29,25].

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 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 and structurally unstable buildings into which it is too dangerous to send humans.

Although full-size helicopters are common today, downscaled vessels are still issues of research. The Institute of Microtechnology in Mainz, Germany, has built probably the smallest flying helicopter [62] (*Figure 5*). It has a length of 24 mm, is 8 mm tall, and weighs 0.4 grams. The rotors are made of painted paper, and the body out of aluminum. The motor that powers the helicopter is 5 mm long and has a diameter of 2.4 mm. The helicopter takes off at 40,000 revolutions per minute, and 100,000 revolutions per minute are reportedly achieved easily. The aircraft has reached an altitude of 134.6 mm.

[2] It is also used for VTOL (vertical takeoff and landing) and tiltrotor airplanes [24].

Figure 5: Micro helicopter made by the Institute of Microtechnology in Mainz, Germany, sitting on a peanut (weight 0.4 grams, length 2.4 cm).

However, this helicopter is not wireless. The lightest remotely controlled helicopter probably is Pixel 2000, made by Alexander van de Rostyne from Belgium [44] (*Figure 6*). It weighs 48.2 grams, and the rotor diameter is 30 cm.

Figure 6: Pixel 2000 made by Alexander van de Rostyne (weight 48.2 grams, length about 30 cm).

The smallest commercially available R/C four-rotor helicopter is Gyrosaucer by Keyence [19] (*Figure 7*). Diameter of the UFO like construction is 26 cm, and it weighs 143 grams. Although it has two gyroscopes that stabilize it, it is still difficult to fly.

Figure 7: Gyrosaucer by Keyence (weight 143 grams, diameter about 26 cm)

None of the described helicopters are autonomous. The smallest completely autonomous vehicle is probably Cypher by Sikorsky [e.g.,13] (*Figure 8*). However, its diameter it 1.86 meters, and it weighs more than 120 kg!

Figure 8: Cypher by Sikorsky (diameter 186 cm, weight around 120 kg).

Since I would like to focus on very small and unobtrusive helicopters, Cypher is just in another league.

The remainder of this paper is organized as follows: There 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 next part, I describe the **basic technologies of a vehicle of the first three phases**, the *Free Flying Micro Platform* (FFMP), in more detail. This includes several **design studies** and a **schematic** of the basic elements. And finally, I will describe the interesting and important features of the last Phase, **Phase 8**.

5 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 and automatic hovering.
- Phase 2: **Flying camera**: for indoor aerial video 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: 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 • Electrical engineering • Aerial robotics • Micro Air Vehicles • 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 • AV technology • 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
4	• Active vision • Simple tasks • Simple morality	• Adding sensors to improve its perception of the environment for human and non-human obstacle avoidance, as well as for evasive behavior • Making it able to understand and carry out tasks like *Come here!* and *Leave me alone!* • 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 • 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 • 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 • Cross cultural Morality	• Improving the intelligence up to *Artilect* stage (artificial intellect, ultra-intelligent machine) [14,27] • Connecting an *Artificial Multi Ethical Advisor System* (Cross Cultural Ethical Knowledge) to make sure its behavior is always ethically correct	**Truly intelligent and highly responsible mobot** (Note that [14] expects such devices realized within two human generations.)	• Neuro Engineering • Philosophy, ethics; expert systems

6 Basic technologies of vehicles of the Phases 1 - 3 and 8

6.1 Phase 1

The FFMP of Phase 1 is appropriate for studying helicopter controls, automatic control systems, and automatic hovering. It is a Micro Air Vehicle (MAV) [65,35], "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" [53]. Therefore, compared to today's R/C helicopters [26], it is smaller (diameter less than 10 inches), quieter (electro motors), safer (rotors hidden in the fuselage), and—most important—it can hover *automatically*.

The vessel of Phase 1 is supposed to be simple: it mainly consists of micro electric ducted fans and an absolute position sensor

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., [7,55,8,29]). Most of these projects use inertial sensors like accelerometers and gyroscopes [16]. 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. Fortunately, absolute position sensing has made much progress lately (e.g., [48,16,63]). 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. The idea is that the rotational movements of the longitudinal and horizontal axis, 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. Given the relatively small size and low price of commercially available absolute position sensors on a radio[3] or ultrasonic basis (e.g., [17]), such a construction would be an elegant solution to the automatic hovering problem[4]. An additional heading sensor (magnetic compass) is necessary for controlling the movements around the vertical axis[5]. However, external 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.

[3] [16] mention that "according to our conversations with manufacturers, none of the RF systems can be used reliably in indoor environments." (pp. 65)

[4] 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).

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

Therefore, other sensing technologies and controlling concepts should be considered too, e.g., on-board vision with Artificial Retina chip sensors (e.g. [32]), detecting optical flow [6].

Propulsion

I propose the use of micro electric ducted fans [38,64]. 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 [2] 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 [31]. An alternative to the ducted fan would be the much more efficient *Jetfan* [23]. However, this technology is not yet available in the requested small size.

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 [26]. 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), or are not yet available [39,34].

Another possibility to consider, especially for earlier phases, would be 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. Yet another option to explore are electrolytic capacitors (Super Capacitors) [e.g., 3]. Wireless Power Transmission [36] would be interesting, but is not an issue yet [7].

The following figures show four **design studies** for an FFMP of phase 1:

- Four ducted fans wrapped in donuts (*Figure 9*)
- Four Ducted Fans in an inflated basketball (*Figure 10*)
- Four Ducted Fans in bedroom lamp (*Figure 11*)
- Four Ducted Fans attached to a tetrahedron (*Figure 12*)
- One Ducted Fan on a stick (*Figure 13*)

[6] "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" [6].

[7] 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 [10,11,9].

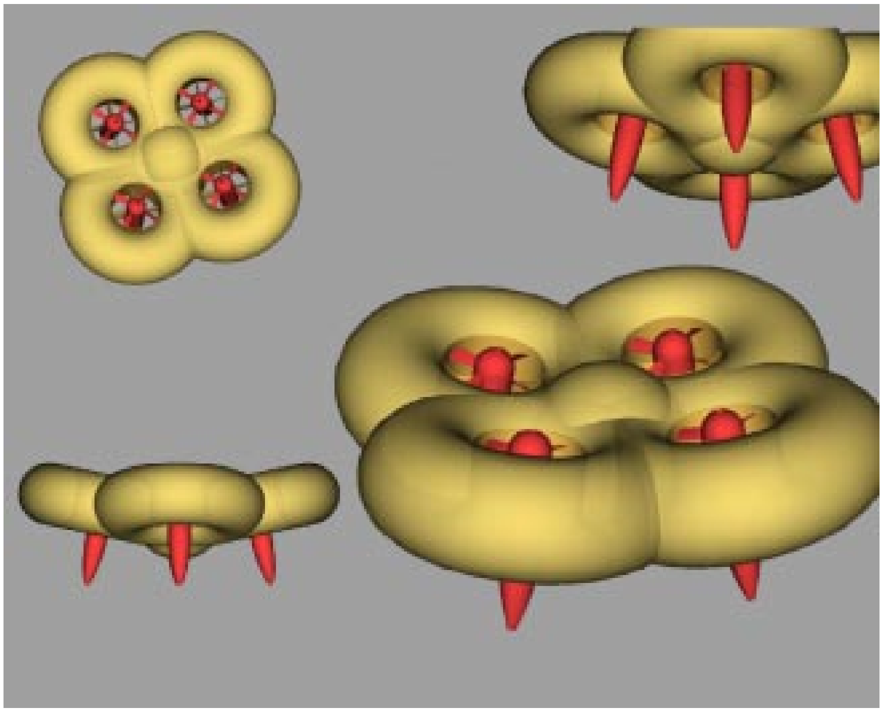

Figure 9: Four ducted fans wrapped in donuts. This idea is obviously UFO inspired. Two of the four electric impellers will run clockwise, two of them counter-clockwise. Like that, the helicopter can be controlled by a combination of speed changes of the four rotors. (The Keyence *Gyrosaucer* and *Engager* [19], as well as the similar *Roswell Flyer* [49] use the same technique.) The donuts can be filled with helium to produce additional lift. Additionally, they act as bumpers or airbags if the helicopter bumps into something. The batteries and the rest of the electronics are placed in the sphere in the middle. (Ken Perlin [24] gave me the tip to tilt the donuts slightly to the center. Like that the vessel will gain stability.)

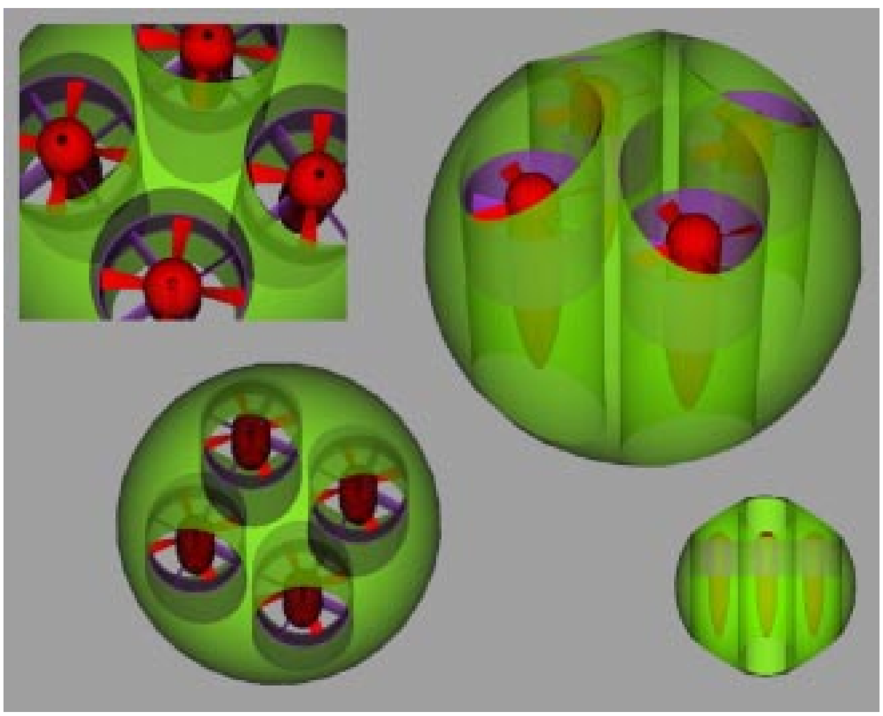

Figure 10: Four ducted fans in an inflated basketball. Another idea was to put the four ducted fans in a sphere. The ball would hide all internal "organs," just hovering "magically." Of course the sphere does not have to be massive: filled with a gas lighter than air increases the lift remarkably. However, there are two problems: first, a sphere takes a lot of space—it makes the helicopter look bigger than necessary. However, it is supposed to be unobtrusive. Second, the center of gravity is in the middle, close to the propulsion units. Because of that, the helicopter would tip over very easily. To prevent that, the control system needs to have a very short "reaction time."

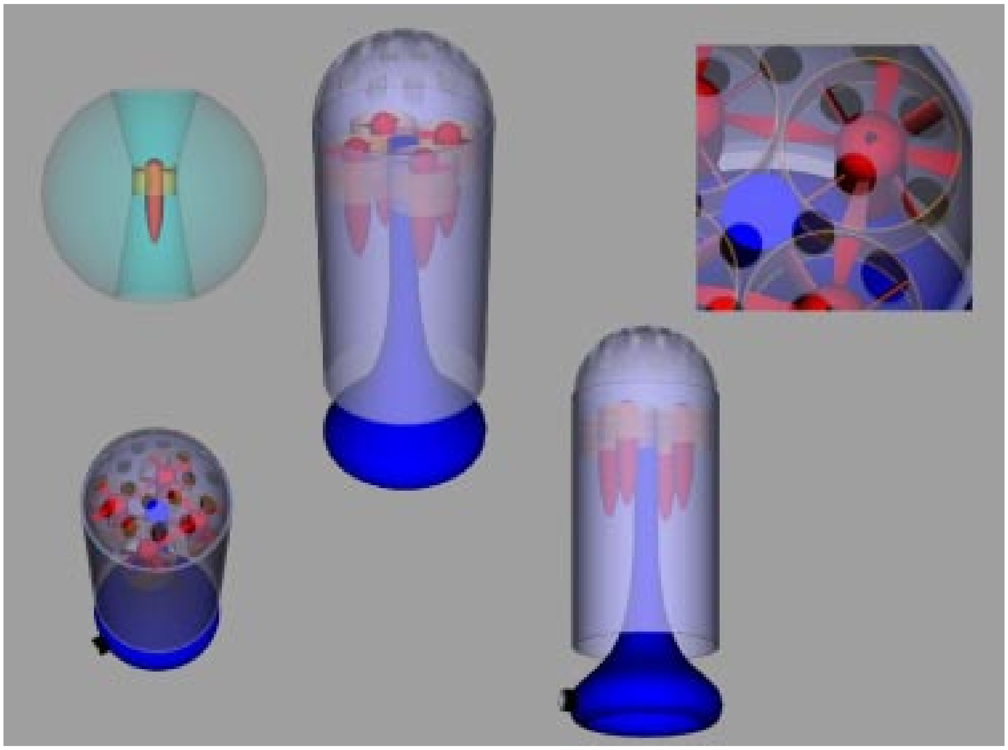

Figure 11: Four ducted fans in a bedroom lamp. The idea behind this design is that the lower the center of gravity, the slower the helicopter will get out of balance. It still won't be stable like that, but roll and pitch changes will not occur as sudden as with a flat vessel like the donuts or the sphere. The purple, transparent hull protects the fans and prevents people from touching the rotors. The batteries and the electronics sit on the bottom of the foot of the "lamp."

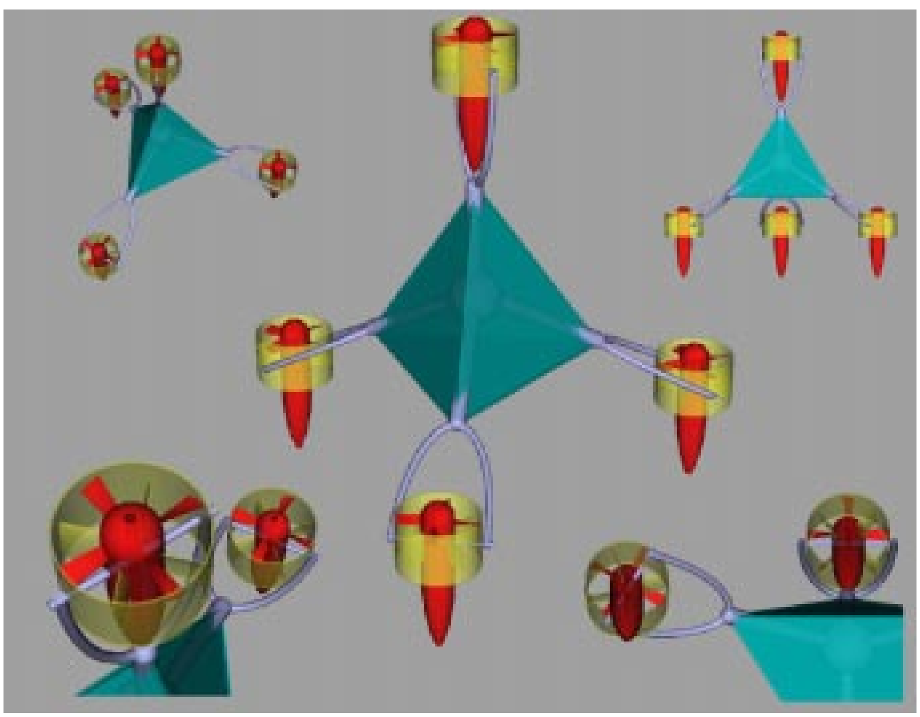

Figure 12: Four ducted fans attached to a tetrahedron. If four impellers are mounted with two degrees of freedom (pan and tilt) in the corners of a regular tetrahedron, the vessel would be very universal and agile—and on the other hand, very unstable. The advantage of such a configuration is that the vessel can roll 360 degrees (there is no top or bottom), and do other unconventional flight maneuvers. Unfortunately, the spiky ends of the ducted fans as well as the air intake openings are not protected. Additionally, rotating the ducted fans and tilting them needs probably very powerful servos. (Thanks to Dan Overholt for the brainstorming.)

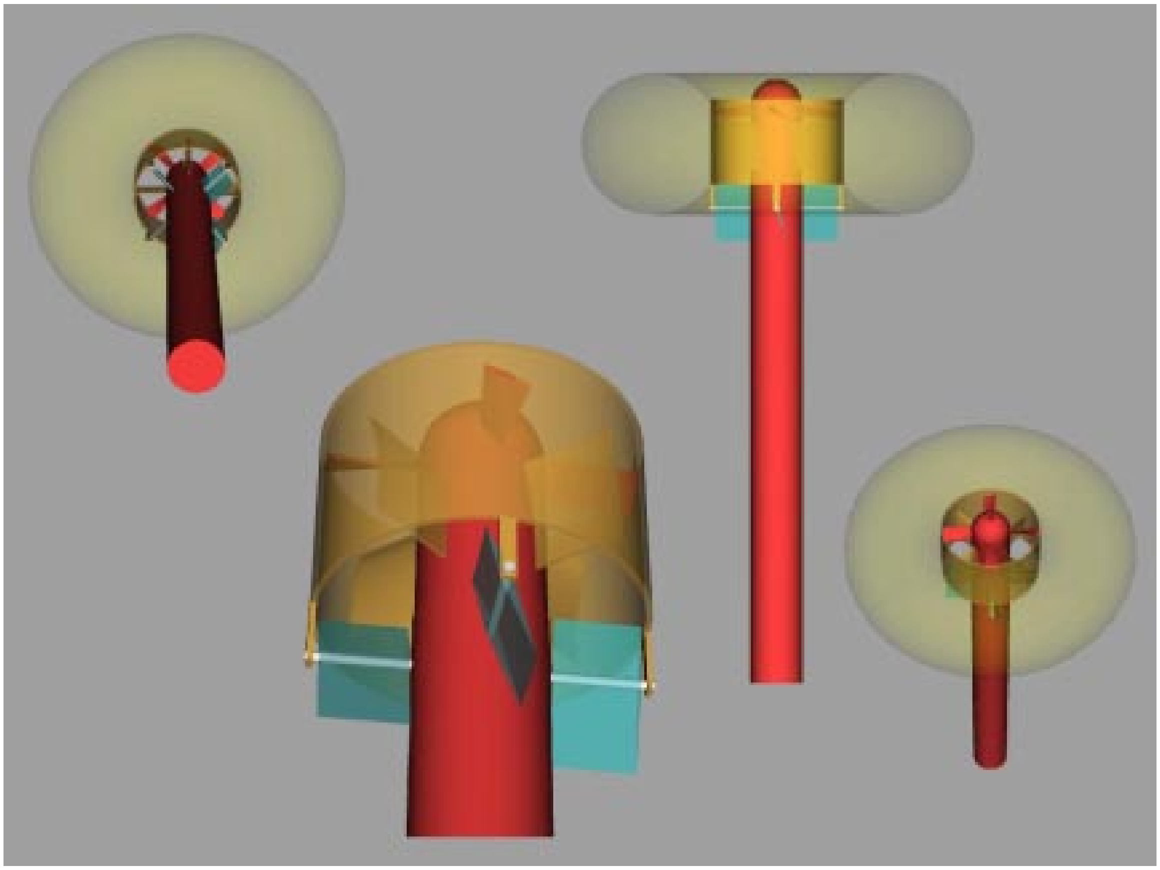

Figure 13: One ducted fan on a stick. After I have heard how loud electric ducted fans are, I thought about concepts with as few as possible noisy engines. I have tested one small ducted fan. I was holding it vertically, and surprisingly, the tendency to yaw—the torque reaction— was not very significant, once the fan has started up. This is probably because the mass of the rotors is relatively small compared to normal helicopter rotors. So I came up with the idea that four small ailerons could compensate for the yaw tendency. The same ailerons could be used to deflect the airflow to move the vessel backward, forward, and sideward. If the mixing of the yaw, roll, and pitch function is made by the control system, four servos are necessary, one per aileron. (However, if there are separate ailerons for the yaw compensation, only three servos would be necessary—but more ailerons.) The battery cells are placed at the very bottom of the tube to keep the center of gravity as low as possible. And again, the donut is filled with air or helium to provide additional lift and to protect the impeller.

Figure 14 shows the schematic of a FFMP of phase 1. (The video camera and receiver are part of a phase 2 FFMP.)

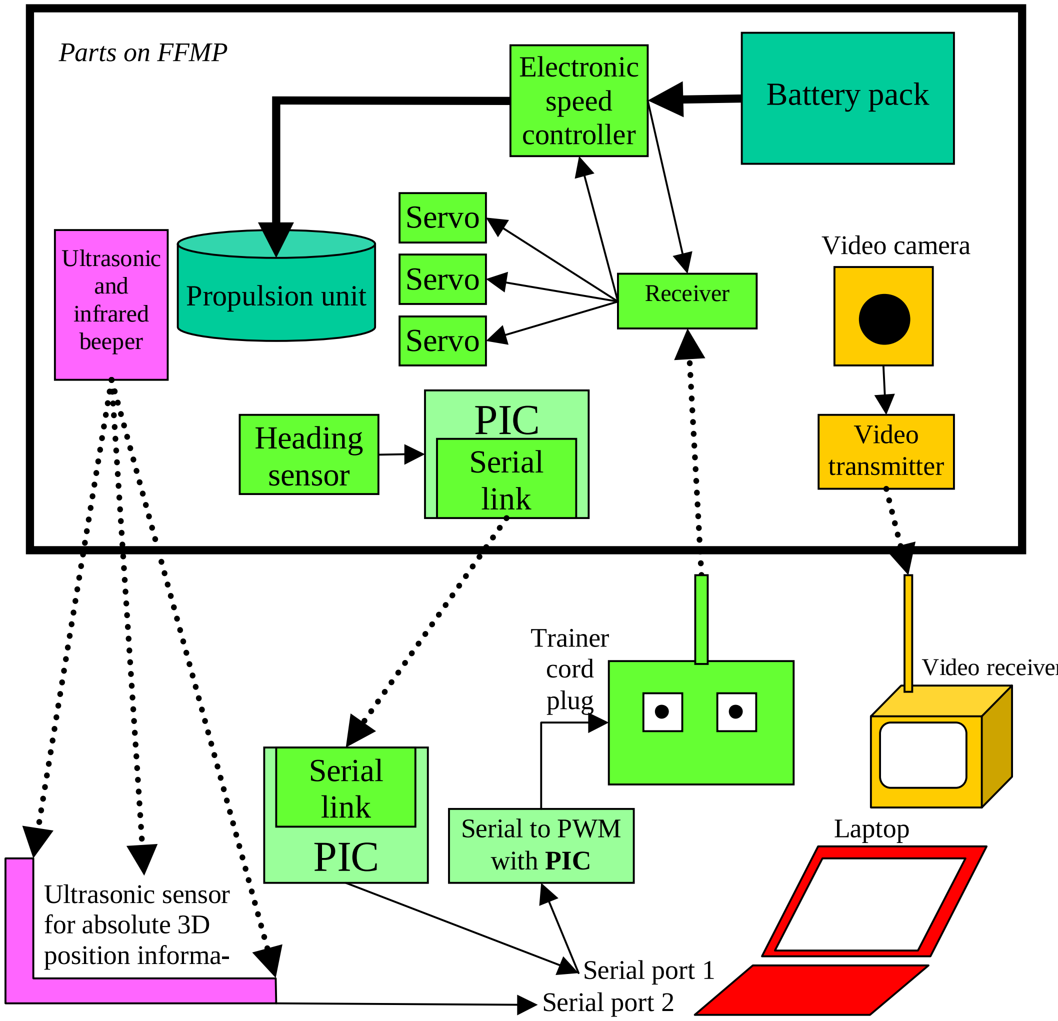

Figure 14: Schematic of an FFMP of phase 1. It is intended to study automatic hovering. Absolute position is measured with a commercially available ultrasonic sensor on the floor, with a range of 1 meter. The position is processed by a laptop, which in turn generates the signals to keep the vessel on its initial position. These control commands are sent via serial port to a PIC that transforms them to pulsewidth modulated signals. These signals are sent via a commercially available radio handset to a receiver on the FFMP. The receiver drives three servos that in turn move the flaps. An electronic speed controller for the propulsion unit(s) is connected to the receiver as well. An additional heading sensor is necessary to determine the heading angle. This information is sent back to the laptop through a wireless serial link. Note that the other two angular positions (tilt and pan) are not controlled directly, but only indirectly by moving the vessel back and forth and left and right. This should be possible since the center of gravity is relatively low and the tendency of the FFMP to flip over is relatively slow.

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 newsgathering (ENG) tasks for live coverage. There is no video processing required in Phase 2; 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 are several commercially available devices that could meet these criteria. *Table 2* shows a selection of currently available board video cameras and video transmitters.

Table 2: Commercially available board video cameras and video transmitters.

Cameras

type	*manufacturer*	*size*	*weight*	*chip*	*horizontal resolution*	*pixels*
PC-17YC	Supercircuits [58]	41x41x20mm	70g	CCD 1/3 in color	450 lines (> S-VHS)	410,000
MB-750U	Polaris Industr. [45]	32x32x23mm	15g	CCD 1/3 in BW	420 lines	251,900
GP-CX161P	Panasonic [40]	26x22x13mm	8g	CMOS 1/3 in color	330 lines (> VHS)	115,500

Video transmitters

type	*manufacturer*	*size*	*weight*	*range*	*frequency*	*output*
MP-2	Supercircuits [57]	51x32x4mm	14g	700–2500 feet	434 MHz	200 mW
AVX 434-mini	Supercircuits [56]	25x17x4mm	9g	1500 feet	434 MHz	N/A
VID24G	Electra Enterpr. [15]	12x12x5mm	4g	2000 feet	2.4 GHz	N/A
C2000	Ramsey [47]	19x19x6mm	2.8g	300 feet	434 MHz	20 mW

Figure 15, Figure 16, and Figure 17 show examples of micro cameras and video transmitters.

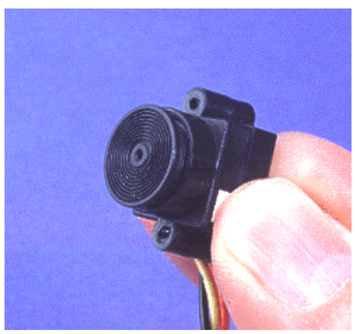

Figure 15: Example for a very small CMOS video camera (Polaris CM-550P, weight 15 grams)

Figure 16: Another very light CCD board video camera (Panasonic GP-CX161P, weight 8 grams)

Figure 17: Example for very light video transmitter (Ramsey C2000, weight 2.8 grams)

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 is possible. The main motivation is to communicate with an autonomous mobot in natural language [54]. Natural language access to autonomous mobots has been studied in detail in the context of land-based robots [33], 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

I also 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., [5,22]). The output is fed into the MIMO system.

Michio Sugeno of the Tokyo University of Technology has built a helicopter [55,25] that is 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” [55]. Although the controlling concept is interesting, this helicopter cannot operate indoors; with its overall body length of 3.57 meters (*Figure 18*), it is far away from the planned size of an FFMP of Phase 3.

Figure 18: A Yamaha R-50 helicopter, overall length 3.57 meters, as used by M. Sugeno for his voice controlled helicopter interface.

Up to now, we have looked at speech as an interface *from* human *to* machine. However, the communication flow between human and machine is probably two-way. What issues come up with the opposite direction: *from* machine *to* human? What kind of feedback would the FFMP give back? What kind of feedback is appropriate?

Coming from the domain of interactive animated characters, **Ken Perlin** [24] proposes to make such devices have the appearance of personality—so that they can *gesture* with their *position* and *orientation* to let people know about their "intentions." He suggests that many aspects of his work with human-directed avatars and computer-controlled agents that interact with each other in real-time, through a combination of Procedural Animation and Behavioral Scripting techniques, are directly applicable to the interaction between humans and FFMP. He is also exploring multi-modal interaction paradigms that combine IMPROV[8] with speech and gesture recognition.

Richard Bolt has done very related work. He suggests *Multimodal Natural Dialog* (MMND), a concept that combines speech, gesture, and gaze to obtain a more natural interaction with computers and robots. Bolt writes,

> "…When we and the computer share common time and space, our speech, gesturing, and gaze become each complementary to the other. That is, information that might be missing in any one of these modalities can be searched for in the others.
>
> For instance, suppose I say to the machine, 'What's that?' Relying upon just words alone, the meaning of that is ambiguous—given that there is more than one item on display, or more than one sound emanating from different spots in audio space.
>
> However, if I am looking and/or pointing toward some particular thing, or in some particular direction, then the machine—provided it has the means to track my eyes and sense my hand position—can combine that information with what I uttered in words, and figure out what it was I mean by *that*.
>
> Specifically, the use of coordinated, redundant modes lessens the burden on speech by permitting gesture and glance to disambiguate and supplement words. Overall, fewer words are needed. Such benefits from multimodal communication can happen not only between people sitting in each others presence in a cafe, but as well between people and computers.
>
> The main benefit from thus combining modes lies in enabling *everyday social and linguistic skills* to access computing power. The computer captures user actions in speech, gesture, and gaze, interprets those actions in context, and generates an appropriate response in graphics and sound.
>
> One powerful result is that of opening up computing power to the non-expert—namely, to most of the world. Dealing with a computer will shift from a purely technical to an increasingly *social* relationship. The user will experience the computer less as a tool, and more as human associate." [46]

> "…MMND provides a powerful, naturalistic command style for real-time interaction with computation, whether that computation be resident in 3-D audiovisual displays, on-screen agents, personal robots, toasters or teddy bears." [46]

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[8] IMPROV is a set of tools and techniques developed at NYU which make it possible to create applications involving animated agents that behave, interact and respond to user input in ways that convey mood and emotion. These tools can be used without prior experience in computer programming, cognitive science or ergonomic simulation, while still allowing creation of animated agents who exhibit behavior which has the lifelike, somewhat unpredictable feel of human behavior, yet remains consistent with a character's personality and defined goals. The goal of the IMPROV project is to make improvisational animation accessible to experts with minimal expertise in animation and dramatic performance, and to enable researchers and educators to exploit these technologies without relying on expensive production efforts. These are clearly two of the most important steps toward the wide-scale acceptance and use of animated agents for education and training, social simulation and collaborative environments.

Bolt does not include mobile robots, but one could say that an FFMP of a later phase indeed could be looked at as a combination of personal robot and teddy bear (…), so his work is highly relevant. Since human and FFMP share the same primary physical space, interactions would be thinkable like "Go over there." As a reaction, an FFMP of a later phase would process the speech, and at the same time detect gestures and/or gaze direction.

Although Bolt obviously cannot address the specific needs of levitating robots that can move in three-dimensional space, many of his points are still valid for FFMP, especially the fact that MMND could be a Win-Win situation for both robots and humans. "The primary gain for the person is the ability to interact with computers via his or her own native equipment rather than in arbitrary, machine-oriented ways. (…) The primary gain for the computer from MMND is the possibility of gesture and glance enabling fewer words to convey meaning, thus reducing dependence upon speech input under conditions of ambient noise, unclear enunciation, and speaker variability." [46]

In any case, it will be interesting to apply the MMND elements to the context of an interface with a levitating robot.

In the following, I will make some comment on the last phase, phase 8. I expect vessels of this phase to become real not earlier than 60 years from now.

Phase 8

Goals for phase 8 are:

- Improving the intelligence up to *Artilect* stage (artificial intellect, ultra-intelligent machine) [14,27]
- Connecting an *Artificial Multi Ethical Advisor System* (Cross Cultural Ethical Knowledge) to make sure its behavior is always ethically correct

Artilect

In this phase, the mobot's intelligence should be on a high level, ideally on an **Artilect** stage. "An Artilect ('artificial intellect'), according to Dr. Hugo de Garis, is a computer intelligence superior to that of humans in one or more spheres of knowledge together with an implicit will to use the intelligence. Artilects are the concern of artificial intelligence specialists (or 'intelligists') like de Garis, who speculates that human society may soon have to face the question of whether and how we can restrain artificial intelligence from making decisions inimical to humans." [14]

"Dr. de Garis assumes that within one or two generations, we will have computers that are more sophisticated than human brains with the ability to experimentally evolve their intelligence into something much beyond what humans might contemplate or understand. De Garis wonders whether such machines would consider human beings important enough to preserve. He speculates that society will soon need to face the question of whether we should permit Artilects to be built. He foresees two factions arising: the Cosmists, who argue that they should be built, and the Terras, believing that they should not. The Cosmists might believe that Artilects would probably want to leave our planet to seek intelligence elsewhere in the universe. The Terras believe that it would be too dangerous for the human race to allow Artilects to be developed." [14]

AMEAS

The second important goal of phase 8 would be to connect or add an **Artificial Multi Ethical Advisor System (AMEAS)**. At this stage, an FFMP has already a considerable amount of autonomy. Therefore, it should be aware of all consequences of its behavior. For this purpose, I suggest to develop and implement an Artificial Multi Ethical Advisor System.

This idea was originally inspired by a Science Fiction movie in which the most ethical being turned out to be an android. Although this situation might sound not very plausible, it is actually not so far fetched if one takes a closer look at the problem. The domain of ethics is not as fuzzy and one might expect. Based on my ethical-philosophical studies at the University of Bern, I think that it is theoretically possible to implement the whole domain of ethics in an expert system. The reason why I think it is possible is that most ethical systems are based on some sort of rule based system anyways.

One of the problems that has to be solved might be related to the fact that most ethical systems are described using a proprietary and incompatible terminology—learning and understanding this terminology is an important step towards understanding the ethical system itself. Therefore, it is possible that ethical constructs of different ethical systems seem to be incompatible, but are the same, just described in different words.

Such and expert system should be able to give advice on complex ethical questions, considering not only *one* ethical system, but *several*. An expert system can contain several ethical positions in parallel. Since there is no "claim for truth" anymore in modern ethical discussions, ethical advice from this system would not be a "right or wrong" answer, but more like suggestions towards a decision as opposed to another one.

Given a simple rule based ethical system like the 10 commandments, a very simple AMEAS would be able to provide pieces of advice like *Do not kill*. However, such an answer would not be specific enough. Therefore, part of an AMEAS would be to provide an understandable explanation for this rule, and based on that, practicable advice in today's world.

Obviously, a simple question for advice has to be submitted together with extensive information about the personal and general situation of the asking person, since ethical advice may depend crucially on individual situational circumstances.

I expect that most people will dislike deeply the idea of "being said by a machine what I have to do, what is good and what is bad for me." However, the AMEAS is not meant to patronize human mankind. Every single person has to be kept responsible for the consequences of his/her decisions—this fact will never change. But in today's multi cultural world where our behavior easily can have global impact, it is nontrivial to consider the consequences of our behavior. E.g., what is appropriate to be put on a homepage on the World Wide Web? What might be perfectly appropriate for one culture might be highly offensive and blasphemous in another one. Therefore, a Multi Ethical Advisor System can give *advice* and *explain* why one decision might be more favorable than another. However, the asking person does not necessarily have to follow this advice if s/he thinks that it is not appropriate. AMEAS just enables people to ask several competent and accepted philosophers like Kant, Socrates, etc. for their advice on an actual ethical problem.

Not much work has been done to set up an AMEAS. However, computer based ethical reasoning systems are described by [18], and a case-based knowledge representation for practical ethics by [4].

In the context of FFMP, having an AMEAS available means that an FFMP can be aware of the consequences of its behavior. If carrying out a request of a human being would violate clearly ethical rules in most ethical systems, the FFMP has to refuse this request. It would be interesting to see if such an FFMP would accept a military mission at all.

There is more information available about FFMP and Papa-TV-Bot at:
http://www.media.mit.edu/~stefanm/FFMP/

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