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The HoverBot — An Electrically Powered Flying Robot

by

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SUMMARY

This paper describes the development of a fully autonomous or semi-autonomous hovering platform, capable of vertical lift-off and landing without a launcher, and capable of stationary hovering at one location. The idea to build such a model-sized aerial robot is not new; several other research institutes have been working on aerial robots based on commercially available, gasoline powered radio-control model helicopters. However, the aerial robot proposed here, called the HoverBot, has two distinguishing features: The HoverBot uses four rotor heads and four electric motors, making it whisper-quiet, easy-to-deploy, and even suitable for indoor applications. Special applications for the proposed HoverBot are inspection and surveillance tasks in nuclear power plants and waste storage facilities.

Without a skilled human pilot at the controls, the foremost problems in realizing a model helicopter-sized flying robot are stability and control. It is necessary to investigate the stability and control problems, define solutions to overcome these problems, and builde a prototype vehicle to demonstrate the feasibility of the solutions. The proposed HoverBot will have eight input sensors for stability and control, and eight output actuators (4 motors and 4 servos for rotor pitch control). The resulting control system is a very complex, highly non-linear Multiple-Input Multiple-Output (MIMO) system, in which practically all input signals affect all output signals. A

surprisingly simple experimental control method, called additive control, is proposed to control the system. This method was successfully used in the current experimental prototype of the HoverBot (although with fewer input signals). It is also proposed to investigate two alternative control methods, adaptive control and neural networks, both of which appear to be especially suitable for the Multiple-Input Multiple-Output control problem.

If successful, the project will result not only in a working prototype of a flying robot, but it will also provide important insight into the functioning of various control methods for very complex MIMO systems.

1. INTRODUCTION

At first glance, the thought of aerial robots might invoke some skepticism. However, a survey of the literature and talks with other universities revealed that not only are aerial robots technically feasible, but also that numerous credible Universities (such as Georgia Tech, CMU, U of Southern California, UT-Arlington) are already conducting serious efforts to develop aerial robots (see Appendix D, video tape).

Fixed-wing unmanned aircraft are being used routinely for military and meteorological purposes and have been in service for years. Typically, these “drones” require mobile lounging platforms and remote operation by trained personnel. The type of flying robot we address in this proposal, however, is quite different. Our aim is the development of a fully autonomous hovering platform, capable of vertical lift-off and landing without a lounger, and capable of stationary hovering at one location. In short: the functional equivalent of a helicopter, only much smaller and, of course, fully autonomous. With this concept in mind, it comes as no surprise that most of the ongoing work on aerial robots is actually done with commercially available model helicopters, marketed for the radio-control enthusiast. The model helicopters undergo extensive modifications [Baker et al., 1992], to make them suitable for autonomous operation and the performance of useful tasks. A guideline of sorts for tasks expected from a working aerial robot has been established with the annual Aerial Robot Competition, sponsored by the Association for Unmanned Vehicle Systems (AUVS).

The more promising aerial robots designed by the above Universities are based on gasoline powered, model-sized helicopters, and research efforts concentrate on designing or down-scaling the autopilots that would stabilize these helicopters in flight.

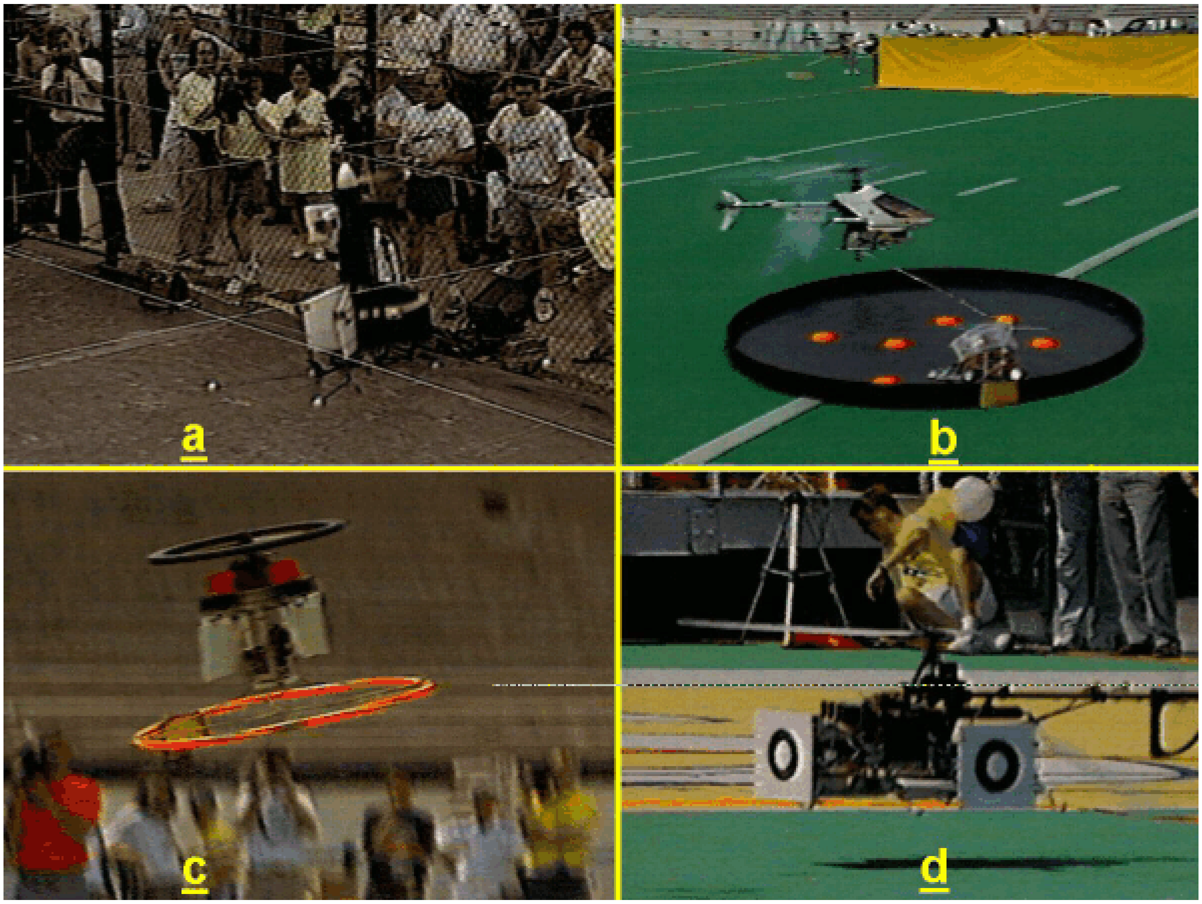

Figure 1: Pictures of a Competition: (following page)

a. Best performance at the 1991 competition: the entry from The University of Texas. Crashed after 6 seconds.

b. Model helicopter with human pilot at the Radio Control. Red disks in gray arena must be picked up individually and airlifted to another ring. (1992 competition).

c. This single-propeller (not rotor) driven craft crashed after 5 seconds in the air: engine failure (1992 competition).

d. Large model helicopter from Georgia Tech. Crashed after 6 seconds. Inertial navigation system failure (1992 competition).

2. STATEMENT OF THE PROBLEM

The foremost problem with model-sized helicopters is stability. All helicopters (large ones as well as model-sized ones) are dynamically instable because of the lack of damping [Saunders, 1975]. In the absence of natural damping (typically found in ground-based vehicles in the form of friction), a helicopter must be stabilized by the pilot. This task is easier for large helicopters, because they have a larger time constant. In model-sized helicopters the time-constant is very small, and stable hovering is difficult to achieve. For this reason, it takes model-helicopter pilots months and months of exercise and training to acquire the skill of manual stable hovering [Tradelius, 1991].

In a robotic model-sized helicopter, the difficulty of stabilizing the craft falls onto the onboard controller. Technologically, this is quite a challenge since the smaller time constants require a much faster response time, which, in turn, requires accurate motion sensors and fast computers. Yet, the model-sized helicopter is severely limited in its payload capacity and can only carry lightweight, less powerful computers and less accurate sensor systems.

In our project we add a further dimension to the challenge by attempting to design an electrically powered flying platform. If successful, an electrically powered device would have very unique advantages for certain applications, because it would be suitable for indoor applications, easy to deploy, and very quite. We envisage applications in hazardous environments in general, and particularly in Nuclear Power plants, where a real need for a hovering inspection unit exists. Other potential applications are emergency response, as well as police and military applications. The only acceptable solution for most of these applications is an electrically powered platform. The disadvantage of electric power compared to gasoline power is the even further reduced payload capacity.

We propose to overcome both the payload problem and the stability problem by implementing a unique four-rotor design. Four-rotor platforms are not a new idea — the history of vertical flight shows several attempts at implementing such designs (the earliest dating back to 1922 [Young, 1982]). As much as these attempts improved the overall payload capacity, they all found themselves discontinued because of the difficulty in manually controlling the four rotors. We believe that our proposed approach, will overcome the problems of earlier 4-rotor designs and bring into existence an actually functioning, electrically powered, fully autonomous 4-rotor flying platform. Our preliminary experimental results to date show that the payload problem, although ever-present in all design considerations, is successfully addressed by the 4-rotor design. The focus of this proposal is therefore the question of stability. We believe that the results of our research will not only help create a flying robot, but they will also have direct bearing on the design of large (people carrying) 4-rotor rotorcrafts.

3. POSSIBLE SOLUTIONS

Here at the University of Michigan we have been working since July 1992 on the design of an experimental prototype of an aerial robot, called the HoverBot. Our design has two distinguishing features: The HoverBot uses four rotor heads and four electric motors, making it whisper-quiet, easy-to-deploy, and even suitable for indoor applications. Figure 2 shows our artist's depiction of the HoverBot; reality is reduced to the smaller inset in Fig. 2, showing our actual experimental prototype during stable[1] hovering. Note that at this time the motion of the experimental prototype is confined by a stationary fixture. This fixture prohibits motion in x and y direction, but allows pitch, yaw, and roll, as well as vertical (z-direction) motion.

In the following Sections we will discuss the HoverBot design in more detail. Our aim is to convince the reader of the feasibility of the concept, and to explain the challenge of the control and stability problems.

3.1 Electrically Powered Rotorcrafts

We propose to develop an electrically powered rotorcraft. To date, electrical power has been found unsuitable for rotorcrafts, except for the very lightest of model-helicopters. The reason for this can be explained with a few first-approximation design guidelines for rotorcrafts (See Fig. 3). As a rule of thumb, the power P required to develop thrust (i.e., lifting capacity) T is given by

$$P \propto \sqrt{T^3}$$

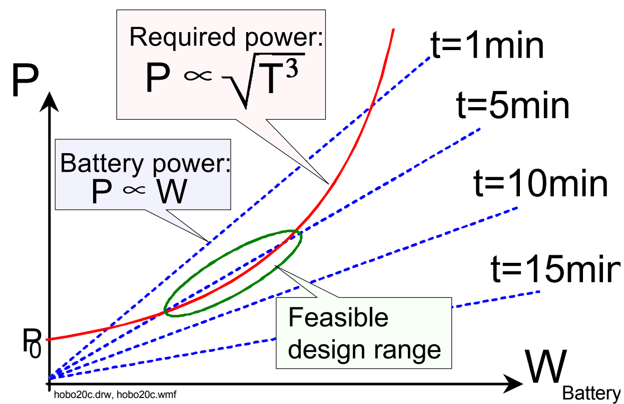

Figure 3:
Power vs. Weigh chart for electric rotorcrafts.

This function is sketched in the Power vs. Weight chart of Fig. 3. The offset P_0 represents the power required for lifting the motors and structure. The battery power vs. battery weight (for a given maximum flight duration) is plotted as a group of dotted lines, each for a given flight duration. Because of the non-linear nature of Eq. (1) electric helicopters cannot be scaled: It is impossible to simply design around a larger motor and larger battery, to get a larger (read: stronger rotorcraft). As Fig. 3 shows in principle, there is only a small range of feasible designs. Commercially available model helicopters demonstrate this principle: only

1 More on this in Section 4 **C** Experimental Results to Date.

extremely lightweight (2 - 3 lb) models with 5-6 minutes flight duration are available. These models use ultra-light building materials and control elements.

A robotic rotor-craft would need an onboard computer and sensors, in addition to the conventional radio-control components. For this reason, we conclude that it is unfeasible to build a robotic rotorcraft based on current electric power model helicopter technology.

To overcome this seemingly inherent limitation, we propose to design a multiple rotor platform, called the HoverBot. In principal, the Hoverbot can be considered as four individual electric model helicopters, linked together at their tails. While this design slightly increases the weight of the structure, its advantage is that certain components needed in every conventional model helicopter (such as gyros and the receiver and its power source) can be shared among the four units, and so can special components for autonomous operation (such as a computer board, more gyros, and other sensors).

In preliminary experimental battery endurance tests, we achieved 3-minute flights with our prototype HoverBot and conventional NiCad battery packs. The tests were somewhat flawed by inferior charging equipment that wouldn't allow optimal charging of the cells. Rotor blade loading, power transmission, and motors were also far from optimal in our early experiments. We expect that by the end of a three-year project, we will have improved on these factors to achieve flight times of 4 - 5 minutes with standard NiCad batteries. More important, new battery technologies promise additional two- to threefold improvements in weight-to-charge ratios. Driven by the rapidly expanding market of notebook computers, more powerful nickel-hydrate batteries are already in use, which provide 1.5 - 2 times higher energy densities, and recently Byte magazine [Byte, 1993, March, p. 24) reported on the development of new lithium-iron batteries that promise 3 times longer operation than Alkaline batteries of the same size[2].

3.2 Four-Rotor Design

In the earlier days of vertical flight experimentation (before the development of the ingenious cyclic/collective pitch concept — which is now used by all modern helicopters) developers looked at the intuitively easy control functionality of 4-rotor designs. While some of these prototypes did indeed fly, none ever made it into production. The reason most often quoted was the fact that the 4-rotor machines were difficult to control and stabilize: With manual controls, the pilot would have to coordinate at least four control parameters (for example, the pitch of the rotor blades), which were rather counter-intuitive (see “principle of operation,” below).

Another reason to consider multiple rotors is to achieve larger pay-load capacities then what is possible with single rotor designs. The reason for this is the fact that the thrust of a rotary wing is proportional to the square root of the area swept through by the rotor. This area is also called the rotor

[2]Ultimately, of course, we are interested in weight-to-energy ratios. Yet, the literature quoted size-to-energy ratios (relative to existing products). We quote these examples here to show the feasibility of electric power, while the focus of the proposal is on the stability and control problem.

disk. I other words, the larger the rotor disk, the more thrust is developed. Obviously, there are technical limitations to the maximal size of the rotor disk. Multiple rotors multiply the effective rotor disk area, although there are, of course, losses. Most notably are losses caused by the additional weight of the structure and losses due to turbulent interaction of the air underneath the disks. Nonetheless, tandem rotor designs are clearly superior to single rotor helicopters in terms of pay-load capacity [Lightbody and Poyer, 1990].

3.3 Control of the HoverBot

The control system of the HoverBot is designed to allow either fully autonomous operation or remote operation by an unskilled operator. To either, the HoverBot will appear as an omnidirectional vehicle with 4 degrees of freedom: (1) up/down (2) sideways, (3) forward/backward, and (4) horizontal rotation.

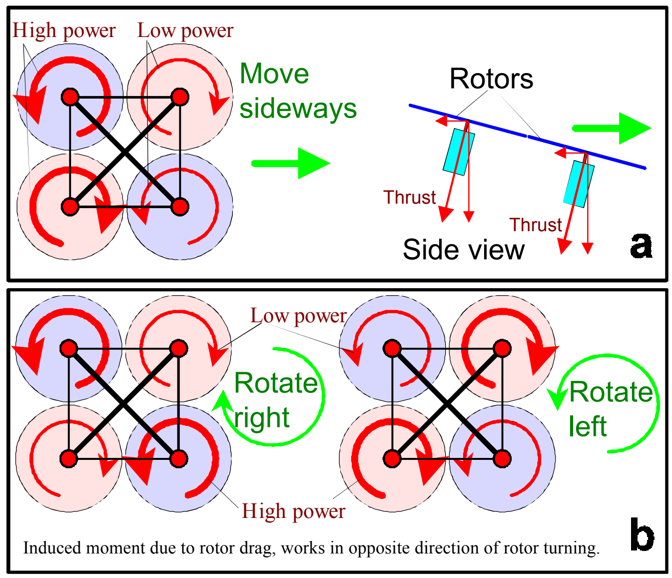

Figure 4: Controlling the HoverBot:
a. More power to the left rotors lifts the left side up and produces a left-thrust.
b. More power to the diagonally arranged rotors rotating in the same direction causes a difference in induced moment.

Up/down motion is easily controlled by collectively increasing or decreasing the power to all 4 motors. Control over (2) can be achieved as explained in Fig 4a: For example, increasing the power to the two left rotors lifts the left side up and generates a thrust component to the left. Consequently, the HoverBot moves to the right. By the same principle, adding power to the two rear rotors causes the HoverBot to fly forward. The implementation of horizontal rotation control is less obvious: When a rotor turns, it has to overcome air resistance. The reactive force of the air against the rotor causes a reactive moment called the "induced moment." The induced moment acts on the rotor in the direction opposite to the rotation of the rotor. As everyone knows, conventional helicopters require the tail-rotor to counteract the induced moment. In the HoverBot both sets of diagonal rotors turn in opposite directions (as indicated by the opposite direction of the arrows in Fig. 4b). As long as all rotors experience the same induced moment, which is mostly a function of speed of rotation and rotor blade pitch, the sum of all induced moments is zero and there is no horizontal rotation. If one set of rotors, for example the one that turns counter-clockwise in Fig. 4, increase their rotational speed or their pitch, the resultant net induced moment will cause the HoverBot to rotate clockwise. It is important to note that because of the diagonal arrangement, this operation has no effect on translation in x or y direction. The effect on up/down motion can be compensated by reducing the pitch or speed of the other diagonal pair, although in practice this is not quite so easy without some sort of feedback control.

In our experimental prototype we were able to implement these control functions with good results. Section 4 discusses the experimental results obtained to date in more detail.

3.4 Stability

We believe that stability is the foremost challenge for any effort to build a model-sized robotic rotorcraft. As explained before, in the absence of natural damping, all rotorcrafts must be constantly stabilized by the pilot or auto-pilot. In model-sized helicopters this presents a formidable difficulty, because of the much smaller time-constants. This is the reason why model-helicopter pilots need months and months of training, just to keep their helicopters in stable hovering. Model helicopter pilots we talked to confirm that stabilizing a small model helicopter is even more difficult than stabilizing a larger model helicopter.

3.4.1 Larger Time-Constant With the Proposed HoverBot

The 4-rotor design of our proposed HoverBot — originally motivated by considerations of payload — appears to have one unique advantage over conventional helicopter designs: the distributed weight of the 4 rotor heads increases the moment of inertial and thereby the time constant of the system. To illustrate this point, we can roughly estimate that the moment of inertia, J, of a 6 kg conventional (single rotor) helicopter model around its longitudinal axis is $J = 0.06\ Kgm^2$. By comparison, the 4-rotor HoverBot with the same weight has a moment of inertia of $J = 1.53\ Kgm^2$ around its least favorable axis. In other words, the moment of inertial of the HoverBot is approximately 1.53/0.06 = 25 times larger than that of a comparable conventional helicopter. Since the time-constant τ of the system is proportional to the square root of the moment of inertia ($\tau \propto J^{1/2}$), the time-constant of the HoverBot is $(25)^{1/2} = 5$ times larger than that of the conventional helicopter design. Stabilization of this rotorcraft will be greatly facilitated by the much larger time-constant.

3.4.2 The Dual Control Approach

Another important advantage of our 4-rotor design is the control flexibility gained from the use of four independent motors. As we explained in Section 3.3, the HoverBot can be fully controlled by controlling the thrust of the four rotors. In conventional helicopters thrust is controlled in two different ways: a) by adjusting the motor power and b) by adjusting the rotor blade pitch (the angle of attack of the rotor blades). Adjusting the motor power is usually not an efficient means of control, because gasoline powered engines do not respond quickly enough (especially with the large inertia of the rotor) to the pilot's commands. By contrast, adjusting the rotor pitch has an immediate effect on the thrust: a larger pitch angle increases the thrust. However, a larger pitch angle also increases the power needs of the rotor and must therefore be accompanied by an increase in motor power. Because of the kinetic energy stored in the rotor, the increase in motor power does not have to be available immediately, a short delay is acceptable. Thus, the immediate action of pitch control combined with the slightly delayed action of motor power control works well. In normal-sized helicopters (without automatic control), determination of the proper mixture between pitch increase and motor power increase is left to the skill of the pilot.

The problem is different in the HoverBot. Here, controlling the motor power is somewhat more effective because we use electric motors. We found that we can perform the typical control functions (up/down, forward/backward and sideways tilting, rotation) just by controlling the rotor thrust. However, in our system the craft must also be stabilized by varying the rotor thrust. In our experimental system we found that the thrust control must react at least ten times faster in order to dampen undesirable oscillations caused by external disturbances. Thus, we propose a dual control approach, in which fast-acting pitch control is the primary means for damping and stabilizing, and motor power control is the primary means for controlling the steady state thrust and thus the motion of the HoverBot.

In practice, both control actions are strongly interrelated. Any control signal going to, say, the front left motor must also generate a secondary control signal that affects the pitch actuator of the front left rotor, and vice versa. The exact nature of this interaction is extremely difficult to determine analytically. The interaction is highly non-linear and there are numerous parameters that are practically impossible to measure. Our focus in the proposed work will be to develop experimentally a new controller capable of performing this complicated stability and control task.

3.4.3 The Control System

The proposed control system requires eight different sensors, as shown in Figure 5. To understand how the system works, we recall that our two primary purposes are to stabilize and control the system. Because of the small time-constants we will need fast-responding sensors to measure the rate of rotation around the three principal axis. These sensors are the three gyros in Fig. 5; they will be used primarily for damping. To control the HoverBot (i.e., to hold it in stationary hover or to move it in a controlled fashion) we need the three accelerometers. These sensors are mounted at the center of the craft and measure the acceleration of the HoverBot in x, y, and z direction.

Theoretically, it is conceivable to use either the gyros or the accelerometers, because the data from either group can be computed from data from the other group. For example: If the HoverBot was ideally built and if there were no external disturbances, then tilting to the right (measured by gyro x) would result in a predictable acceleration, velocity, and translation to the right. In reality, however, it is likely that even in the absence of measurable tilting there will be sideways thrust components that will accelerate the craft sideways (because of construction tolerances and external disturbances). Conversely, we believe that the accelerometers cannot substitute for the immediate response of the gyros to tilting. Extensive experimentation will be required to validate or invalidate these assumptions.

Additional sensors are the ultrasonic height sensor and the fluxgate compass. The height sensor will be used near ground level, to provide very accurate height information (on the order of a few millimeters [POLAROID, 1993]). The fluxgate compass provides accurate heading information ± 0.5 degrees if no disturbing magnetic fields are present. Again ,the fluxgate compass cannot replace gyro θ because of its slow sampling time (on the order of 0.4 sec [KVH, 1993]).

The signals from all eight sensors are constantly sampled by the main control block, labeled multiple input multiple output (MIMO) in Fig. 5. The MIMO block computes control signals for all eight outputs: four motors and four pitch controllers. To implement complete control and stabilization, each output is affected by all eight inputs, resulting in a matrix of 8×8 non-zero elements in the MIMO control block.

Attempts to solve similarly complex control problems for conventional model helicopters are currently under way; Schwartz and Klir [1992] report on the use of fuzzy logic controllers and Lewis et al. [1993] report on work in progress at Purdue, where Ahmad applies Neural Networks. In previous work with MIMO controllers [Borenstein, 1992, 1993] and in our prototype HoverBot (discussed in Section 4) we have had good results with an approach we call additive control. This approach is described in Section 4, using the example of the prototype HoverBot.

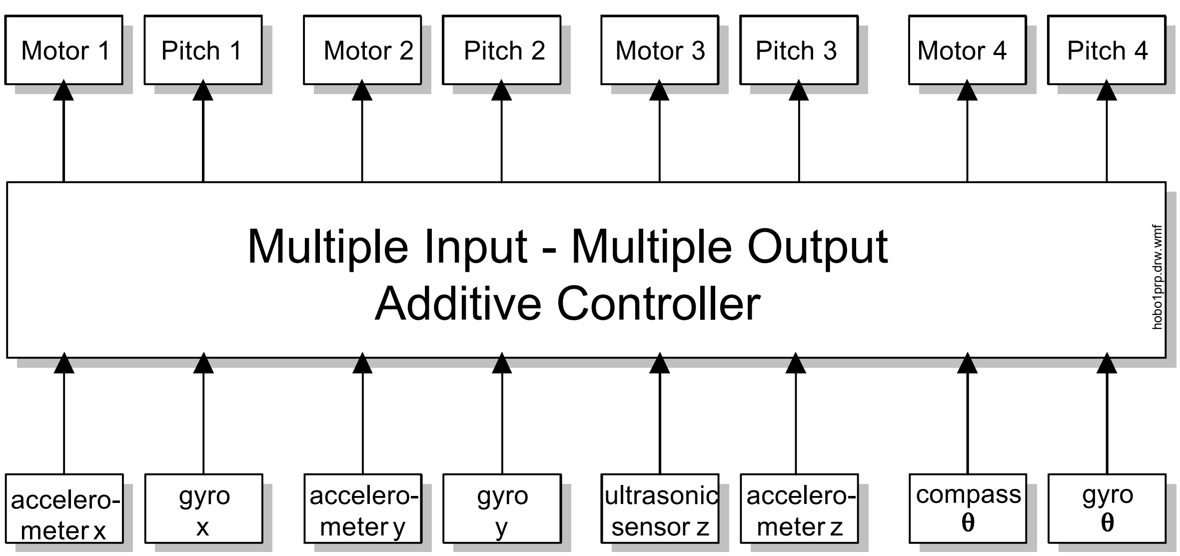

Figure 5:
Eight sensor inputs and eight actuator outputs are interconnected in the HoverBot control system.

4. EXPERIMENTAL RESULTS TO DATE

Figure 6 shows the HoverBot prototype during stable hovering, 4-5 inches above the floor. The fan in the background corner is captured in this picture to enhance the viewer's perception of airflow disturbances. In reality, the effect of the fan is negligible compared to the turbulence created by the four rotors in the vicinity of the walls. These turbulences are so powerful that loose sheets of paper would fly all over the room. We report these conditions here to make it clear that our prototype HoverBot achieved stable hovering under conditions of intense turbulent disturbances. We believe that our preliminary experimental results have proven the controllability of the HoverBot and indicate that stability can be achieved in the system.

Figure 7 shows the current control system for one of the four motors. Identical control units are implemented for the remaining three motors and for the four pitch control servos. The feedback signal for

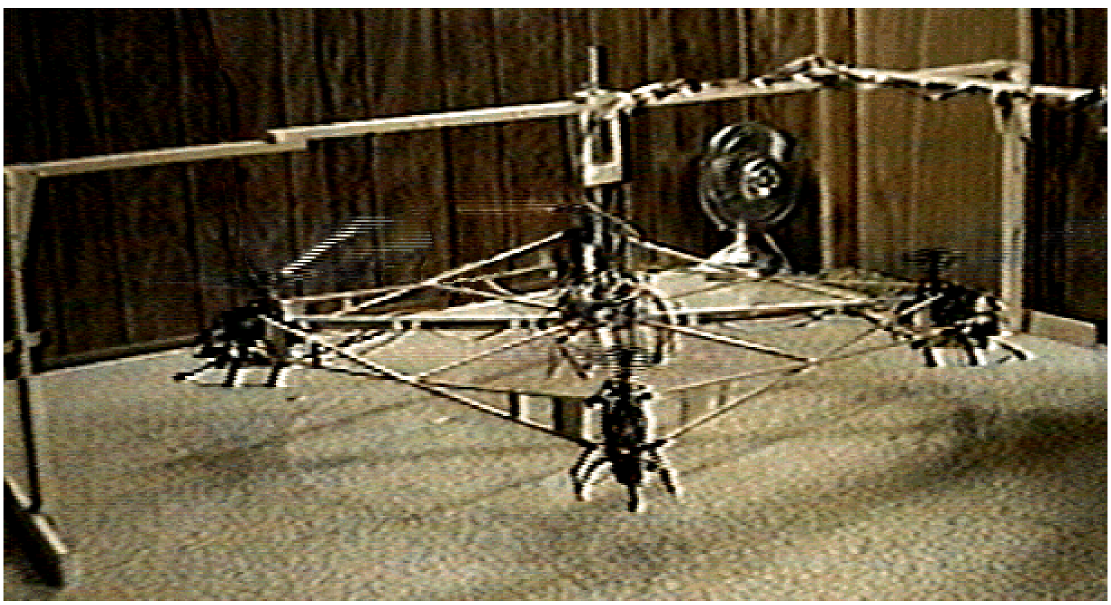

Figure 6: HoverBot during stable hovering. Stationary fixture inhibits horizontal translation (x and y direction). Pitch, yaw, and roll, as well as vertical motion, are enabled. We have built the experimental prototype HoverBot shown in Fig. 6. In order to avoid damage to the craft during experimentation, the prototype is fixed in a stationary fixture which inhibits translation in x and y direction but permits pitch, yaw, roll, and vertical (z-direction) motion. We have implemented control over the four motors and their rotor blade pitch (i.e., control over all eight output actuators is implemented). We have not yet implemented the accelerometers nor the gyros. Instead, we derive feedback data on tilting in the x and y direction from a computer-game joystick. This joystick is mounted at the center of the HoverBot and connected through a vertically sliding and freely rotating shaft to the stationary framework shown in Fig. 6. In addition to the angle measurement capability, the joystick provides an inexpensive ball-and-socket joint for a total of four intersecting axis of motion. The MIMO control system from Fig. 5 is partially implemented: the joystick readings provide relatively fast angular position (tilt-x and tilt-y) information, from which rate-of-rotation information can be computed to emulate the readings from gyro-x and gyro-y. We have also installed a fluxgate compass which helps stabilize the orientation of the HoverBot (although its 0.4 sec sampling time is too slow for adequate damping).

height control shown in Fig. 7 is not implemented. The reference signals are sampled by the computer from a 4-channel radio-control unit. The experimenter can use the dual-joystick radio-control transmitter to control height, orientation, and tilting in x and y direction. Fig. 7 explains our current implementation of additive control. In additive control the control signal (in Fig. 7, the motor speed) is the result of adding up different branches of inputs. For example: Suppose that at some time the left front side of the Hoverbot is higher than the right side, but lower than the rear side. Because of this tilt in x-direction, the additive controller will reduce power to the left front motor. Because of the simultaneous tilt in y-direction the tilt-y sensor will increase the power to this motor. Simultaneously, the rotation sensor and the height sensor may add or subtract power. All this adding and subtracting of signals takes place in one sampling interval (20 ms) and results in a single motor speed command being sent to the motor. Intuitively, one may not be convinced that the result of all these additions and substraction is a useful control signal. Yet, our experiments show that the HoverBot can simultaneously perform all these corrective actions.

The best way to get an impression of the performance of the Hoverbot prototype is to watch the first 5-minute segment of the video tape, which is submitted with this proposal as Appendix D.

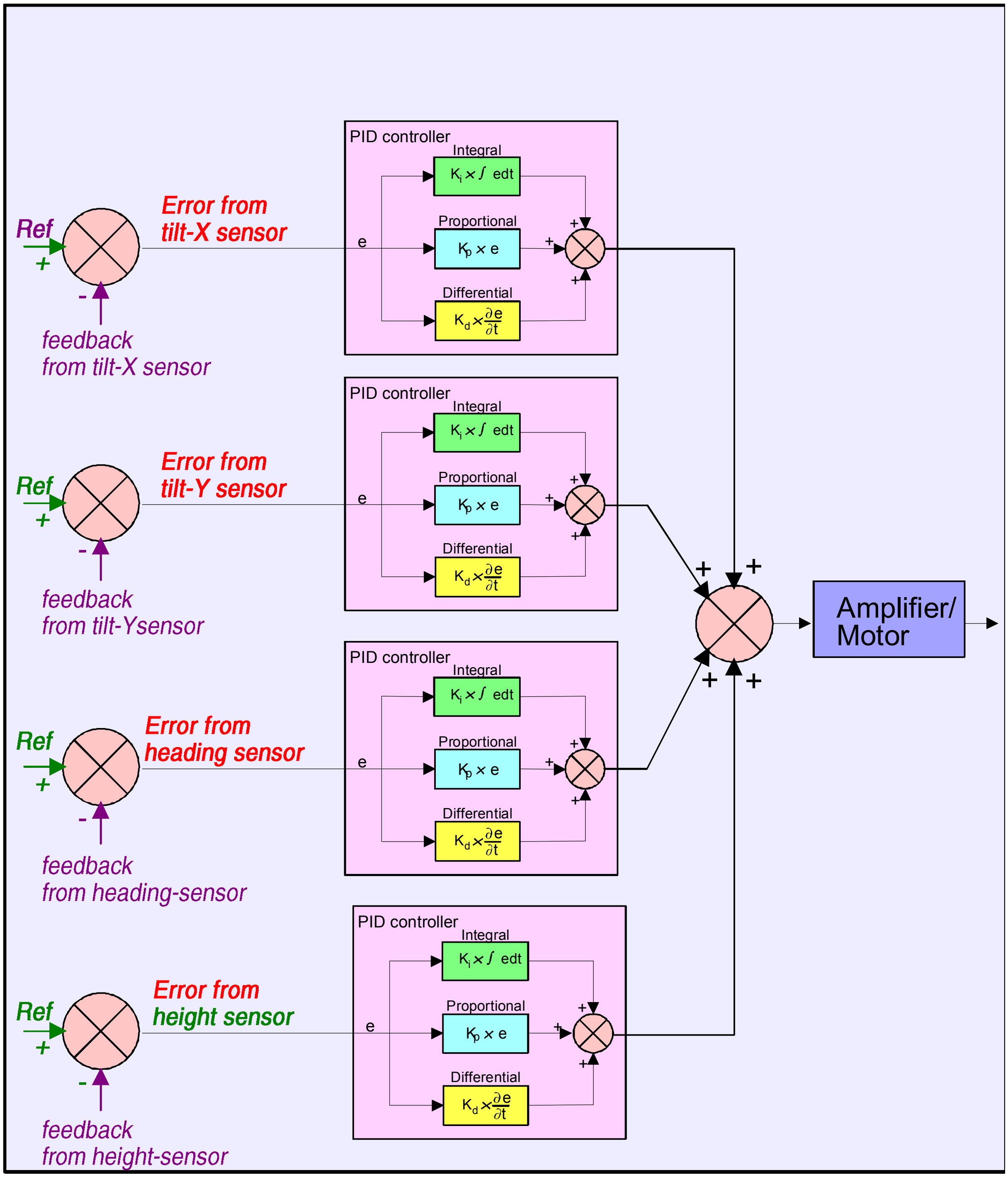

Figure 7: Additive control system in the experimental prototype.
Four different feedback signals are fed into each actuator. The Hoverbot has eight actuators.

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