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Paper:

Flying Robot with Biologically Inspired Vision

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An autonomous helicopter controlled by biologically inspired vision detects the displacement of altitude with real-time video processing, using has 2 CCD video cameras to see landscape objects and processing circuitry with an FPGA. Each image is divided into 800 areas for edge detection, used to detect displacement. Each of these small areas works as an ommatidium, i.e., the compound eye of an insect. In a typical indoor setting (objects such as desks, walls, etc.) visual feedback was not sufficient to realize stable hovering, but additional external feedback helps keep the unstable robot in more stable flight.

Keyword: CCD, FPGA, Brain-type computer, Autonomous optical flow, Helicopter

1. Introduction

We are building small robots that have complete stand-alone processing systems, that use the concept of a brain-like computer,$^{1)}$ and that can move autonomously in complex natural environments. The most difficult aspect of developing a vision for a robot that moves in natural environments is how to reduce the information quantity without losing important features of the scene. Fortunately, the vision processing mechanism of an insect was detailed by the pioneering work of physiologists.$^{2\text{-}3)}$ An insect eye consists of a 2D array of miniature photoreceptors and objective lenses, which all deliver their electrical output signals to the brain in parallel. These signals are analyzed with lateral interactions in a neural network of the medulla and converge on direction sensitive motion detecting neurons in the lobula plate. An insect uses these neural activities to navigate and control flight. If we can mimic these processes by using lightweight electronics that are small enough to be lifted by a model helicopter, we can realize an autonomous standalone flying robot. However, human technologies, especially solid-state semiconductor technologies, are very different from biological processes in the way they work. Our robot uses 2 CCD image sensors with wide-angle lenses instead of compound eyes, because of the difficulty of manufacturing such eyes. The fully parallel neural networks found in an insect's brain are replaced by a partially parallel, partially pipelined digital processing circuit that is built with a field programmable gate array (FPGA).$^{4)}$ The vision processing system we have developed converges rotational and translational velocity data from three-dimensional features found in natural and/or artificial scenes, like an insect's brain does.

2. Implementation

The smallest commercially available model helicopter ("Revolutor"; Keyence, Osaka, Japan. Weight: 120g, Ro-

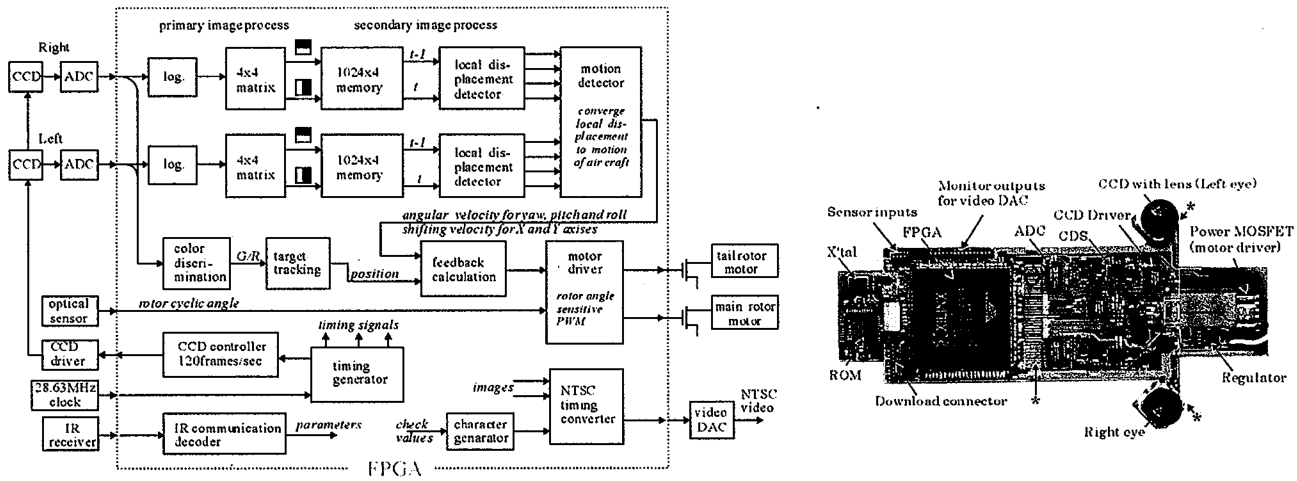

Fig. 1. Block diagram of internal circuit of FPGA and peripherals and a photograph of printed circuit board

tor diameter: 350mm) was selected for the mechanical component of this study. It uses a very unique technology to control the cyclic pitch of the main rotor. It can control the cyclic pitch even though it has no servomotor. The stock helicopter has a printed circuit board (PCB) processing system that consists of a rate gyroscope for yaw stability, a free gyroscope for horizontal stability, and a digital radio receiver for control. We replaced the helicopter's PCB with the processing circuit we developed, which consists of 2 CCD image sensors,[5] their drive circuits, 2 10-bit analog to digital converters, a motor driver, and a 600K gate FPGA as shown in **Fig.1**. The processing PCB must be less than 33g if it is to be lifted by this small helicopter. The FPGA implements the timing generator, CCD controller, primary image processor, secondary edge and local displacement detector, motion detector, and motor controller, as shown in **Fig.1**. The CCD controller drives the CCD chips at 120frames/sec., which is double the normal operating speed. In primary image processing, a linear gray scale is converted to a logarithmic scale, and detection of edge orientation in groups of 4×4 pixels (32×25 blocks per image). The edge-detected image is stored in a frame memory that consists of block-RAM in the FPGA, as shown in **Fig.2**. This frame memory stores only 2bits for each small area. A local displacement detector compares the frame memory contents of refreshed (edge image of time t) and stored (edge image of time t-1) frames to find spatiotemporal correlation. An image is divided into nine (a 3 by 3 grid, each area consisting of an 8 by 8 block) partial areas for the next level of processing. The motion detector uses a majority of the 64 data blocks of local displacement data to distinguish angular velocity from complex optical flow in each partial area. For example, yaw rotation generates uniform horizontal displacement in any part of an image, whereas horizontal shift shows up on the left side and right side of an image. Ideally, the rotational and translational (shift) values of the visual scene can be separated from convergence data using 2 sets (left and right) of partial area data. The resolution of feature detection is about three degrees, and the range of angular velocity detection is 0-360degrees/second. Outputs of the motion detector might be seen as corresponding to the outputs of motion detecting neurons in a lobula plate of an insect brain. Even this works ideally, it can only detect velocity, but it cannot detect position. To realize positioning, brightly colored red and green artificial objects are placed in front of the helicopter. These colored objects are used for target tracking by keeping a constant distance from them. This target tracking method is totally artificial but was necessary to achieve flight. Values from the motion detectors and the target trackers are fed into the feedback calculation section. This section uses a calibration matrix that computes the difference between camera observations and outputs the desired motor control signal to the motor driver. In the future, the calibration matrix might be able to be tuned by neural network methods, but we tuned it by hand for this study. The helicopter has just 2 motors for control. One drives the main rotor, which is made of a flexible plastic, and other drives tail rotor. Power pluses applied to the main rotor motor cause pulses of acceleration in the rotor. These acceleration pulses cause the pitch of the flexible main rotor to change. Changing the timing of these power pluses, relative to the rotor cyclic position, is used to control the cyclic pitch of the main rotor. The rotor cyclic speed is about 30 cycles per second, and 6V at 4A of electric power is necessary to lift the whole body. For debugging, we also integrated an infrared (IR) receiver with a decoder to tune system parameters. An NTSC timing converter is used to monitor images, and a character generator provides visual feedback checking of calcu-

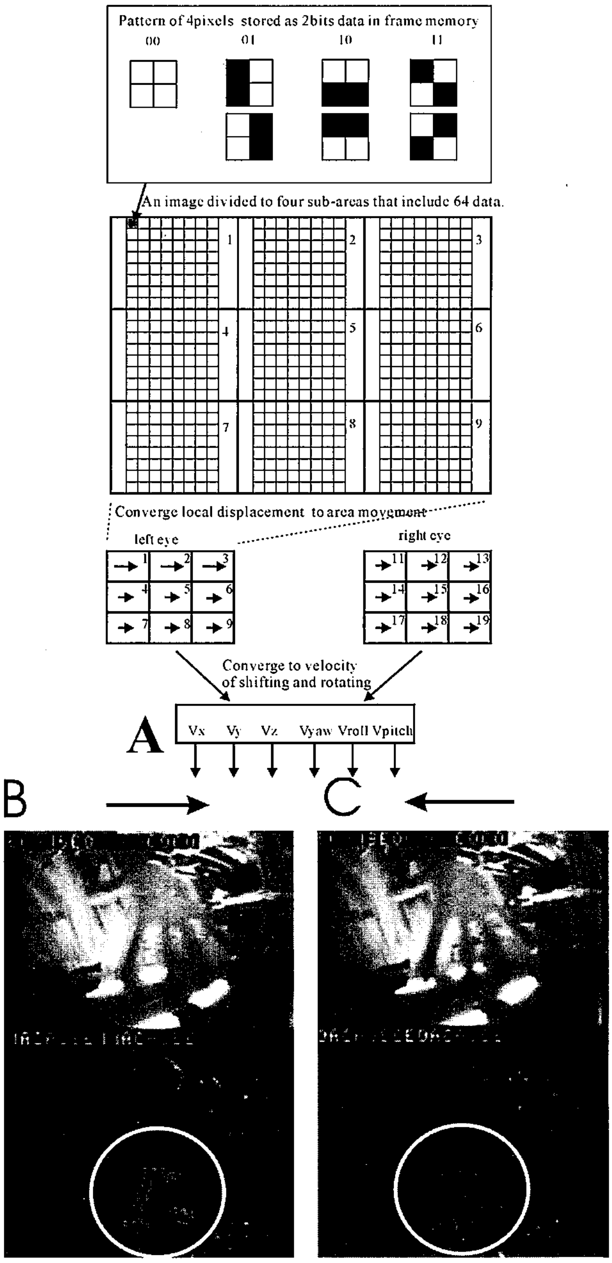

Fig. 2. A: Schematic diagram for image processing of the robot. B and C: Pictures of actual processed images. The hand moves left to right in B and moves right to left in C. The local displacement detector responses are displayed in lower panels. White dots indicate left to right, black dots indicate right to left. As pictures, noises come from blinking of room florescent illuminations are detected also.

lated values. A photograph of the helicopter and the colored target objects are shown in **Fig.3**.

3. Result and Evaluation

The biologically inspired local displacement detector can detect movement of optical system even such easy processing. If we adapt computational image processing, like optical flow detection and using mathematical equations, a processor needs more power and weight clearly. Advantages of hardware biologically inspired vision processing are low power and weight in this study. At least, simple one direction movement gives accurate output. In case of complex movements, outputs of motion detector are almost proportion to degree of angular velocities, but separation of angular velocities from shifting velocities is not perfect. This error can be compensating by using target-tracking outputs, because shifting gives error of position by integration of time. The helicopter embedded on three-dimensional movable test-bench is well feed-backed and it seems can fly.

Using the helicopter we developed, we tuned the parameters for hovering and did autonomous flight-testing. Through our best efforts, the results were not as good as we would like. The helicopter cannot hold a static position in flight, and is always moving around a complex orbit, despite even delicate tuning. In most cases, it loses control suddenly and collides with the floor. The helicopter stayed airborne for about twenty seconds during the longest flight. It seems like a very short time that the feedback system works to stabilize the flight, but if the helicopter did not have a feedback system it could fly no longer than a second. So twenty seconds is not such a short in one sense, but it is far from satisfactory. We analyzed the reasons why it cannot hover by tuning the system parameters, changing the processing circuit, or modifying the body mechanically. We found three main reasons for this:

3.1. Resolution is not High Enough

Because the system circuit has limited resources, only 800 blocks of edge and displacement data are available for detection. This data gives us about three degrees of resolution. We believe that this helicopter needs at least one-degree of visual feedback resolution. In the case of a housefly, the resolution is about 1.5 to 2.5 degrees. It is especially difficult to get an accurate estimate of altitude from the on board camera system because a small change in angular tilt position of the camera causes a large altitude error. It seems as if the helicopter needs another independent sensor to measure altitude.

3.2. Separation between Angular Velocity and Shifting Velocity is not Enough

The helicopter has 2 eyes and about 180-degrees of view. If the cameras detect images of objects located at opposite positions (near 180degrees), the processor can compute the most accurate separation, but if the cameras have no sight of objects located at opposite positions, signal separation is very difficult from the remaining data in images. An insect, like a housefly, has more than 270degrees viewing angle, which is a very reasonable design for signal separation.

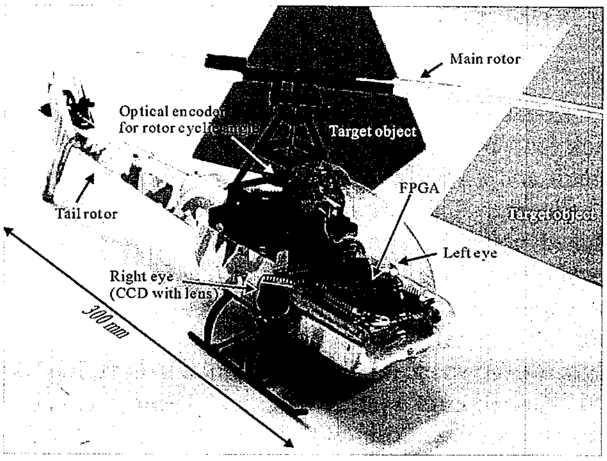

Fig. 3. Helicopter and target

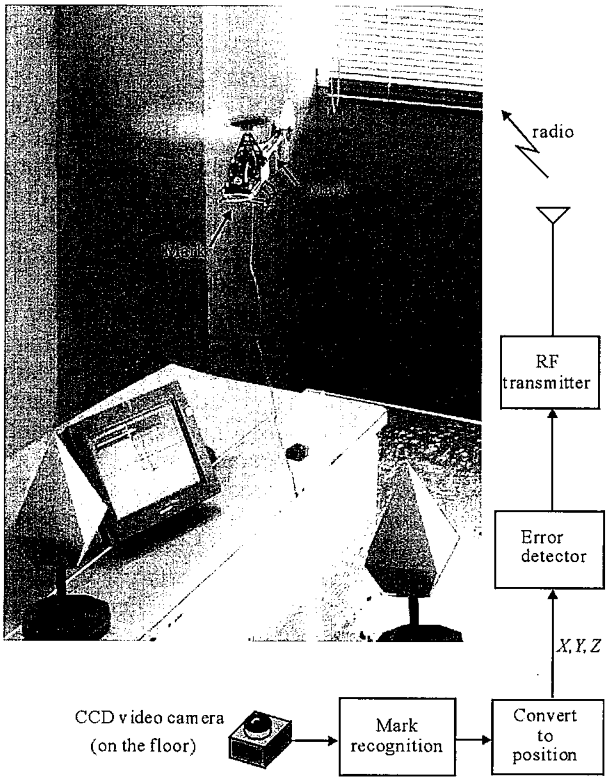

Fig. 4. Flight guided by external feedback

3.3. Collision is Caused by Mechanical Instability and Power Limitations

In some cases, even if the feedback system is working well, the helicopter cannot recover its altitude position because of limited power. The helicopter loses buoyancy in such cases. It seems that mechanical instability amplifies feedback errors, which then become a critical situation. A learning system is necessary to suppress instability by making more intelligent control decisions. Also, fundamental changes should be made to improve the strength of the main rotor and body.

4. Modification

To achieve hovering, we adopt external visual feedback loop by radio control. We put a similar processing circuit and a CCD video camera on the floor just under a helicopter. This external processor observes 2 marks slicked under helicopter from floor and send error of positions by radio. The helicopter that is guided by this radio signal can hover as long as we like. This feedback loop is very efficient to improve stability of hovering. **Figure 4** shows the modified helicopter in hovering state$^{6)}$ and illustration of system overview. Using this external feedback loop, we can correct practical parameters even with incomplete on board processing system.

5. Conclusion and Perspective

We demonstrated a biologically inspired flying robot using a small indoor helicopter. Even though it did not complete its desired goal of autonomous hovering, problems are noted for improving its performance with modifications to its design, and by evaluation of flight and collision data. We are improving the helicopter according to points discussed in the last section.

We concluded that this helicopter is too small for implementing an intelligent system that exhibits free movement with obstacle avoidance. We are developing larger flying robot with 4 propellers, 4 video cameras, and a processor that consists of an SH-3 microprocessor and 4 FPGA chips. One of the video cameras views the ground and it will have the ability to recognize symbols on the floor to measure altitude. The body is made from carbon fiber composite to reduce mechanical instability without any weight gain. A 4-propeller system is very suited to fit with theoretical dynamics than the helicopter cyclic pitch control is. We believe it will be able to complete this study in the near future.

References:

1) I. Ichikawa, H. Yamada, and G. Matsumoto: Realization model for brain computing, Appl. Math. and Comp. Vol.111, pp.193-202, 2000.
2) A. Riehle, N. Franceschini: Motion detection in flies - Prametric control over on-off pathways, Exp. Brain Res. Vol. 54 (2), pp.390-394, 1984.
3) N. Franceschini: Engineering applications of small brains, FED J. 7, suppl.Vol. 2, 1996.
4) Data sheet of Vertex, http://www.xilinx.com
5) Data sheet of ICX076AK, http://www.sony.co.jp
6) Vdeo available on, http://brainway.riken.go.jp

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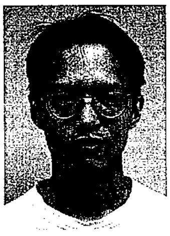

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