Proposal to Department of Electrical Engineering Undergraduate Research Program

Title:

GYRE: Evaluation of Visual Navigation Techniques for Autonomous Free-Flying Robots

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Abstract

Efficient processing of video imagery is an important concern in the design of robots with autonomous navigation systems. In order to further investigate possibilities for visually cued robotic navigation, particularly in freefall environments, the GYRE Reduced Gravity Robotics project is building an autonomous free-flying robot capable of orienting itself using visual cues and navigating in a microgravity environment. To increase the performance of the system the current onboard single CPU computer will be replaced with three single-board computers . The image processing code will be rewritten to run in parallel across all three boards, using an onboard Ethernet network for communication. The increased image-processing performance will be measured directly and will positively contribute to servoing performance in tests aboard a reduced-gravity flight sponsored by NASA's Reduced Gravity Student Flight Opportunities Program in 2004.

Goal

The goal of the GYRE Project is to determine whether or not visual servoing, in conjunction with cold gas thrusters, can provide adequate station-keeping, stabilization, and maneuverings capabilities for use in microgravity environments, and to explore the performance of different visual servoing algorithms for this purpose. Specifically, GYRE 2 in 2004 will compare the performance of two control algorithms, one based on PID and one based on lead-lag. The funding requested in this proposal will be used to cover expenses associated with upgrading the onboard computers of the GYRE robot to enable higher-performance servoing during the GYRE 2 flights, and rewrite the control software accordingly.

Significance

The GYRE Project is significant because it is among the first attempts to apply visual servoing techniques to freefall environments. Its results may aid in the design of future low-cost microsatellites and freefall autonomous robots for use aboard the International Space Station or other on-orbit environments.

Furthermore, our exploration of the applicability of general-purpose image processing techniques to visual servoing may provide information and techniques useful for non-microgravity environments. These could include underwater applications and unmanned aeronautical vehicles.

The RGSFOP, sponsored by NASA's Johnson Space Center, provides a unique and prestigious academic experience for undergraduate students, allowing them to propose, design, fabricate, fly and evaluate a reduced gravity (free fall) experiment of their choice. Undergraduate teams from universities all over the country compete for one of twelve annual flights, making the selection of our proposal an honor and an indication of the quality of our potential research and its value to the fields of robotics, image processing, and microgravity work. This work demonstrates the cutting-edge multi-disciplinary robotics research conducted at UW to both a local and national audience, while highlighting the university's commitment to undergraduate education and community outreach.. We have, and will continue to present our research (and the robot) at schools, museums, and other locations in order to educate the public and encourage interest in science and scientific research. The final results of this project will be submitted to peer-reviewed journals.

Prior Research

Proportional-Integral-Derivative (PID) controllers are widely used in electronic appliances, and are frequently used to respond to visual input, such as aiming a robotic vehicle at a specific point on the road (Tsugawa). PID controllers are usually used to aim a closed-loop system at a specific goal. The Ziegler-Nichols frequency response tuning method (Ziegler) provides a means of tuning the parameters of the PID controller.

Phase Lead/Lag compensators are most often used to shape the long-term behavior of a system into a desirable equilibrium. They are used in visual servoing to maintain a condition such as keeping a vehicle a certain distance from the road's centerline (Blasi). They adapt well to systems with a lot of sensor noise because they increase the margin of error and allow a closed loop to remain stable even in the event of poor decisions caused by bad data, incorrect modeling, or disproportionate system response. We expect to adapt a phase lag in order to cancel out the spikes from the noisy vision algorithms, using the methods outlined in Xu's "Automatic Tuning of Phase-lead and Phase-lag Compensators."

Other prior research incorporates the physics, navigation, control and propulsion design for microgravity robots. Existing research focuses on navigation for ground-controlled systems (Choset et al., 1999; Borst and Volz, 1998). Micci and Ketsdever discuss propulsion specifically for small free-flying bodies (Micci and Ketsdever, 2000), and Kotenkamp demonstrates command architectures (Kotenkamp et al., 1998) for a space-based camera system controlled from the ground.

Technical Approach

Our prior work, GYRE 1, flown aboard NASA's KC-135 Weightless Wonder during July of 2003, validated our visual extraction algorithms. However, performance was poor, at about 3 frames per second (fps). The onboard computer used for this was a commercial laptop with a single Intel Pentium III processor clocked at 800 megahertz. GYRE 1 was supported in part through an Undergraduate Research Grant from the University of Washington Department of Electrical Engineering.

Robot Description

The equipment consists of several off the shelf commercial laptop computers, commercial 802.11b wireless networking cards, an off the shelf digital camera, and a fabricated robot. The robot has the form of a cube 45cm in side length and massing about 20kg. Each edge is a structural section of 1"x1"x0.125" 6061-T6 aluminum angle stock, covered with padding. Cameras protrude slightly from the centers of three faces of the cube and thrusters emerge near two edges of each face. The robot will be propelled by 12 cold gas thrusters, fed by compressed air at 1.3 MPa. The air is stored in two 1.4L tanks at 30.0 MPa and regulated to 1.3MPa with a pressure regulator to ensure that thrust will be consistent throughout the mission and that sufficient supplies of air will be onboard to complete the mission. Each axis has 4 thrusters to allow for both rotational and translational maneuvering.

The current robot uses a commercial laptop with a single Pentium III processor clocked at 800MHz. To improve performance without exceeding our weight limitation, we wish to replace this with three IB760 single-board computers from Anova. Each IB760 has a Transmeta Crusoe processor clocked at 800MHz. Each board will be mated to a Cardbus IEEE1394 interface to control one camera. The boards will communicate over 100mbps Ethernet. The robot's control algorithms will be rewritten to operate in parallel across all three boards, with communication and cooperation over the onboard LAN.

It is necessary to use single-board computers because the robot must meet a 50 pound weight limit to qualify for NASA flight. Commercial solutions of the requisite speed are not optimized for weight, or include functionality we do not require (such as the LCD display and keyboard on the current laptop), and are thus too heavy.

Once the new computer systems have been integrated and the code revised, the performance of the visual processing of the new system will be analyzed (to determine how many frames per second can be processed) and the performance compared to data from the previous system. This will be done using video generated on a test stand. The results of both systems should be identical; only the performance should change. Also, the battery life will be evaluated and compared to previous data, and the change in weight measured.

Experiment Description

In flight, we will test two closed-loop controllers, one based on PID and one based on lead-lag, to see which is more effective at bringing the robot to a stop. There are two primary metrics for success: error and system response. The error is the final speed of the robot – ideally, zero. System response is the amount of time it takes the closed-loop control to reach a steady equilibrium. Each of the robot's three axes will have its own closed-loop controller, which will take input from the two cameras that point perpendicular to that axis (and are thus situated to detect motion around it).

The robot will determine its velocity relative to the aircraft visually, and act, using its compressed air thrusters to counteract that motion, to come to a stop relative to the aircraft and maintain that attitude. We will introduce the robot into various unusual attitudes and compare its response time with different control algorithms. During each microgravity interval, the robot will choose a visual processing algorithm, be positioned by investigators in the approximate center of the available cabin space, impart a moment to itself, then attempt to cancel that moment and perform station-keeping. Moments will be imparted in 0, 1, 2 and 3 rotational axes as well as 0, 1, 2 and 3 translational axes, incrementally. For each microgravity period, we will measure the time taken by the robot to come to a relative stop, assess its effectiveness at station-keeping, and observe and document errors made by the system. This information will be used to determine the most suitable control algorithms for this application. In addition to our own observations, we plan to use a digital video camera mounted to the plane to independently record the movements of the robot for additional accuracy and later analysis.

Work Breakdown

Because we have been working on the robot since 2002, the work for this project consists mostly of assembly, testing, integration, documentation and assessment.

Task	Person or People Responsible
Procure IB760 computers	David, Matthew
Procure Cardbus Firewire cards	David, Matthew
Fabricate mounting hardware and integrate to robot	David, Amelia
Document mounting hardware and perform structural analysis as required by NASA	Amelia, Matthew, Lee, Adam
Design, fabricate and integrate power-control subsystem	David, Matthew
Revise software to run on multiple networked CPUs	Lee, Matthew, Adam
Assess performance	David

Schedule

All tasks are linearly dependent on tasks listed before them in the table.

Task	Start Date	Completion Date
Procure IB760 computers	Jan 5, 2004	Jan 14, 2004
Procure Cardbus Firewire cards	Jan 5, 2004	Jan 14, 2004
Fabricate mounting hardware and integrate to robot	Jan 30, 2004	Feb 10, 2004
Document mounting hardware and perform structural analysis as required by NASA	Feb 10, 2004	Mar 10, 2004
Design, fabricate and integrate power-control subsystem	Jan 30, 2004	Feb 30, 2004
Revise software to run on multiple networked CPUs	Jan 5, 2004	Feb 30, 2004
Assess performance	Feb 30, 2004	Mar 10, 2004

Budget

Category		Amount
Student Salary		$0
Supplies and Materials		$3126
Services		$0
Equipment		$0
Travel		$0
Other		$0
	Total:	$3126

Justification

Supplies and Materials

Supplies and materials include various metal stock from Online Metals to fabricate mounts, as well as wiring and connectors to fabricate the power control subsystem, estimated at $100 based on the team's prior experience; three Cardbus Firewire cards at $100/each (per OrangeMicro), $300 total; three IB760-8A single-board computers at $690/each (http://store.yahoo.com/anovamicro/ib7601.html), $2070 total, and additional lithium-polymer battery cells, 32 at $20.50 each (fmadirect.com), $656 total.

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