AC 2008-1741: SENIOR DESIGN PROJECT : A ROBOTIC SYSTEM USING STEREOSCOPIC CAMERAS FOR NAVIGATION

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SENIOR DESIGN PROJECT: A ROBOTIC SYSTEM USING STEREOSCOPIC CAMERAS FOR NAVIGATION

Abstract

This paper describes a senior design project involving eight undergraduates split into two teams: (1) a computer vision based navigational control team and (2) a robot vehicle design team. Each team was tasked with a specific goal relative to completing the project. The computer vision team's goal was to develop an embedded stereoscopic vision system that will observe the scene around the robot and automatically provide navigational controls to the vehicle. The robot vehicle design team's goal was to develop a robotic system capable of navigating coarse terrain given a sequence of navigation of commands.

Each team had to accomplish a series of intermediate tasks in the process of their design. For the computer vision design team, intermediate design tasks included examination of real-time operating systems (RTOS), sensor selection, and algorithm development. Specific educational outcomes of the computer vision aspects of the design project included (1) understanding the theoretical models of camera image formation, (2) developing models for 3D surface geometry necessary to implement a stereo reconstruction system, (3) software implementation of digital camera Linux drivers, (4) algorithmic time and space requirements for stereoscopic reconstruction algorithms and (5) power-sensitive design for embedded digital signal processing systems.

For the robotic vehicle design team, the primary tasks included building the mechanical part of the vehicle, adding sensors and computing hardware, and developing movement algorithms. Specific educational outcomes of the vehicle design aspects of the project included (1) understanding pulse width modulated (PWM) motor controllers, (2) power considerations in mobile computing designs, (3) Linux device driver programming, and (4) RS232 hardware communications design.

This paper describes the experiences of the split-team project, including successes and failures. Also included are recommendations to senior design faculty on how to organize and mentor such projects.

1. Introduction

This project consisted of two groups of four undergraduate students in the Department of Electrical and Computer Engineering at the University of North Carolina at Charlotte. The combined project goal was to design and construct a robotic vehicle capable of performing navigation using a pair of digital cameras. This was a particularly difficult challenge, as it required a highly diverse set of skills applied in concert that integrate to create compatible components of a complex device.

The project was proposed to and subsequently sponsored by the NC Space Grant Consortium, and administrator of funding for NASA.

Team 1: Stereoscopic Sensor Design Team

The computer vision half of the project sought to build an instrument that can reconstruct 3D models of a terrestrial surface from images generated by a pair of digital cameras, also known as stereoscopic 3D reconstruction. This topic has been a major focus within the field of computer vision for more than 30 years[1] and has been thought about for almost a century[2]. In fact, primates devote about half of their cerebral cortex to processing visual information[3], which may help explain why completing this task using a digital computer is computationally difficult. With applications for both lander spacecraft and rover spacecraft, stereoscopic reconstruction instruments have become critical components to robotic spacecraft.

Stereoscopic Reconstruction Background

Specifically, a stereoscopic reconstruction instrument estimates 3D (x, y, z) positions of objects viewed by a pair of digital cameras. By knowing or estimating the image formation properties of each camera, their relative pose, and the pixels pair in each digital image that correspond to a specific 3D surface location one may invert the image formation process and find the 3D locations responsible for reflecting the light sensed by the camera[1]. Several problems arise in obtaining accurate 3D estimates, which have prompted an explosion of reconstruction techniques (the text by Ma, et al[1] is entirely devoted to this subject and discusses in excess of 40 significant publications on this problem). This is due to the extremely large number of variables involved which, in addition to the geometric problem discussed previously, include *photometry,* i.e., how the scene is illuminated and how surfaces viewed within the scene reflect that illumination, and *environmental dynamics,* i.e., the dynamics of the environment through which both the illuminating light and sensed light passes.

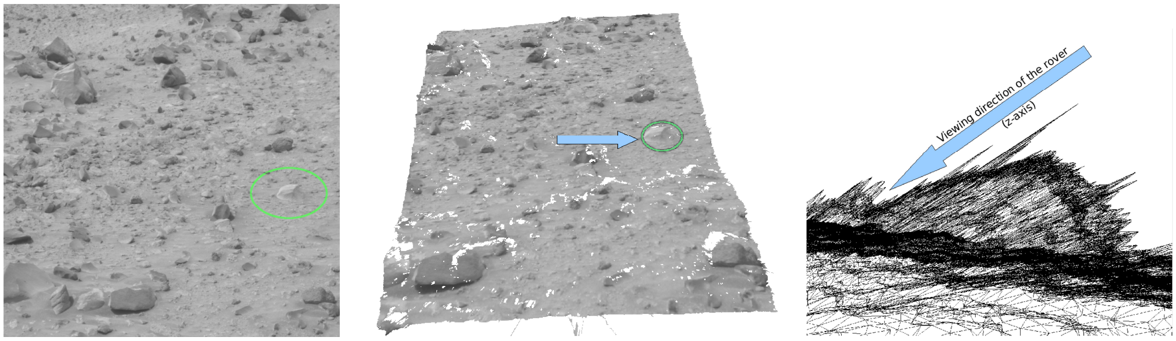

Figure 1: Figures (a-c) detail errors in stereoscopic data produced from a near-field stereoscopic image pair from Spirit on solar day (sol) 672. Fig. (a) shows the left Pancam image from the stereo image pair. A region of interest including a rock is highlighted in the right middle of the image. Fig. (b) shows the 3D surface with the left image superimposed as texture onto the 3D surface with the same region highlights. For Fig. (c) the view is changed to align with the arrow in (b) to visualize depth errors. Fig. (c) shows the rock surface from this perspective as a 3D wireframe model. One can see reconstruction errors as sharp peaks on what is apparently a smooth rock surface in the image. These errors are most pronounced in the direction of the observing cameras, denoted as the depth or z-direction (*generated from Planetary Data System XYZ RDR file: 2p186026346xylajqvp2260l2m1.img using software written by Andrew Willis*).

The most general approaches to the problem seek to estimate many of these parameters and generally have difficulty achieving high accuracy without using a large number of images to constrain the values of the unknown variables[4,5]. However custom-designed spacecraft include very detailed knowledge of many of these parameters that serve to constrain the problem and, when used properly, greatly simplify the solution[6]. This simplification translates into a reduced computational complexity for generating 3D data from a pair of 2D images and many such systems exist today both commercially, e.g., Point Grey Research sells two such systems: Bumblebee2 and Digiclops[7], and for space research, e.g., the Mars Exploratory Rovers (MERs) Spirit and Opportunity[8,9].

NASA is currently operating numerous robotic spacecraft and in the process of building many more to meet their goals for deep space exploration, explicitly mentioned as part of strategic goal 3 of NASA's overall strategic goals[10,p.8]. For Mars exploration alone, the Phoenix Mars lander will be launched in August of this year and includes the Surface Stereo Imager (SSI) built by the University of Arizona and the approved Mars Science Laboratory (MSL) mission is to include another stereoscopic imaging system, MastCam, which is in the design phase at Malin Space Science Systems[11]. Design specifications for the MSL Mastcam include stereoscopic 3D reconstruction of 1200x1200 images at 10 frames per second (fps) with zoom cameras capable of up to 10x magnification[11].

In addition to the lander and rover missions, the computer vision instrumentation proposed is also appropriate for *any* short-range measurement system and could be used on manned spacecraft missions to produce surface measurement data for hard-to-reach locations on any manned or unmanned spacecraft. The Neptec LCS instrument is one example of such a system which used active triangulation, a different version of computer vision based 3D reconstruction, to generate 3D measurements of the Shuttle Thermal Protection System (the heat shield tiles) during the Discovery's "Return to Flight" STS-114 mission in August 2005[12]. The success of such instruments in these varied applications makes it likely that enhanced versions will be needed in the future.

Team 2: Robotic Vehicle Design Team

The operational functionality of the vehicle was identified to be:

1. The vehicle should be able to receive information about the 3-D world.
2. The vehicle should be made to make decisions regarding hazard prevention and path routing from "suggestions" from the vision hardware.
3. The vehicle should be designed to withstand terrestrial conditions.
4. There should be a minimum ground clearance of 0.5 feet in order to navigate terrain and hazards.
5. The overall size of the vehicle should be small enough to deploy in and around structures located on the University of North Carolina at Charlotte campus.
6. The vehicle should be designed for low power consumption.
7. The vehicle should have the option of being remotely controlled.
8. The vehicle should be battery powered and battery replacement should take no more than five minutes.

2. Methodology

Stereoscopic Sensor Design Methodology

The instrument components include a DSP, a FPGA, and two CMOS image sensors with motorized zoom lenses mounted on a mechanically actuated platform. The processing unit proposed is an Analog Devices Blackfin evaluation board (BF561) that includes two low-power Blackfin DSPs (having ADSP-BF535 cores). An FPGA daughterboard will directly connect to the BF561 and will house purpose-built algorithms to provide both computational and power savings. A modified version of the open-source operating system Linux called *uClinux* will run on the processors and manage the algorithmic execution and data flow to generate 3D surface position estimates. Two CMOS imaging sensors connect directly to the BF561 similar to that shown in Fig. 2. Each camera will have a zoom lens with motorized focus control. The cameras and their lenses will be mounted on an actuating platform that varies the angle between the cameras to maintain a common field of view for the camera pair over the zoom range. Both the zoom lenses and the actuating platform will be controlled by the BF561.

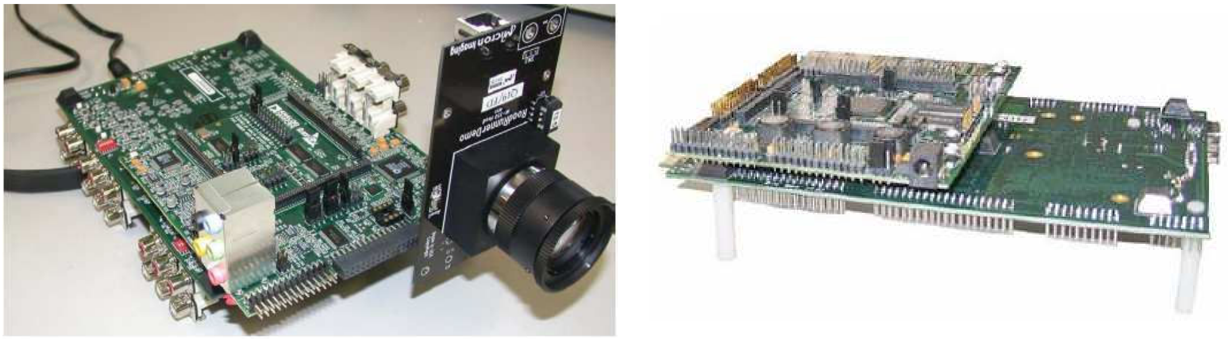

Figure 2: Fig. (a) shows the Analog Devices (BF561) DSP Evaluation Board directly connected to a Micron CMOS image sensor through the one of the two available PPI (Parallel Port Interfaces). Fig. (b) shows the FPGA daughter board that includes a Xilinx Spartan III FPGA with 1M gates (images from Analog Devices application notes and manuals).

For the computer vision design team intermediate design tasks included:

1. Implementing a real-time operating system (RTOS) on an embedded microprocessor.
2. Selecting and purchasing imaging sensors.
3. Implementing the image sensor software drivers needed to collect scene images.
4. Calibrating the image sensors for stereoscopic reconstruction.
5. Implementing the stereoscopic reconstruction algorithm.
6. Processing the resulting 3D data to provide navigational inputs to the developed robotic system.

Specific educational outcomes of the computer vision aspects of the design project included (1) understanding the theoretical models of camera image formation and 3D surface geometry necessary to implement a stereo reconstruction system, (2) software implementation of digital camera Linux drivers, (3) algorithmic time and space requirements for stereoscopic reconstruction algorithms and (4) power-sensitive design for embedded digital signal processing systems.

Robot Vehicle Design Methodology

For the robotic vehicle design team, these tasks included:

1. Build a wheeled robotic platform from off-the-shelf parts.
2. Develop electromechanical drives and circuits to allow autonomous propulsion of the vehicle.
3. Build an FPGA-based processing board that interfaces with the Image Processing FPGA Board(s) and environment sensors (light, acceleration, compass, bump, and sonar).
4. Develop algorithms that translate image knowledge and sensor measurements to path planning, complete with in-course path modification.
5. Test the system on flat and angled terrain with existing obstacles.

Specific educational outcomes of the robotic design aspects of the project included (1) understanding pulse width modulated (PWM) motor controllers, (2) power considerations in mobile computing designs, (3) Linux device driver programming, (4) RS232 hardware communications design.

3. Results Achieved

As is typical of ambitious senior design projects such as this, the teams fell short of accomplishing all their stated goals. This section of the paper describes the results of the teams' efforts.

The final design of the vehicle (Figure 3)[13] included two microcontrollers that collected data from, two ultrasonic sensors, two infrared sensors, one digital compass, and a GPS for navigation. The microcontroller could also receive information about the 3-D environment, in the forward direction of the vehicle, from the BF561 Black-Fin Digital Signal Processing (DSP) Board. After processing all of this data, the vehicle would implement its decisions via the two motor controller circuits (one for each pair of left and right motors).

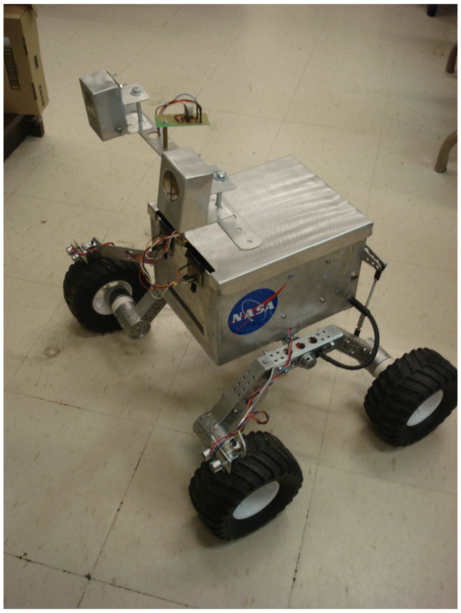

Figure 3 – Completed vehicle design. This device can autonomously move and avoid large objects in its path.

While the Stereoscopic Sensor Design Team attained many impressive advances and learned much about their topic, they were unable to complete the goals of their part of the project. In fact, they were only able to capture rudimentary images, and were unable to complete any recognition algorithms. They did complete simulation of image recognition using MATLAB, but were unable to process images in real-time.

The vehicle team was able to construct a vehicle that could respond to the proposed output from the Stereoscopic Sensor board, however their design was not FPGA-based and it did not implement any path planning or travel history.

4. Lessons Learned: Approaches for Senior Design

The size of the project team, disparate areas of work, and diversity of problems presented in this senior design project present a formidable task both for student organization and for faculty management. This section is devoted to discussing the organization and team management / communication processes adopted for this project evaluates successes and failures in this design and provides some comments on how to better manage such projects.

Leadership: One task of the teams was to create the requirements of their part of the project[14], as assigned by the Senior Design course faculty. While they were able to identify some of the requirements, they had difficulty determining the boundaries of their efforts. Initially, these two teams worked independently and did not consider the logical, electrical, and communications interfaces between the two parts. Further, the groups did not have a good grasp of where the "dividing line" of the two projects should lie. After a few weeks of discussion and with little progress to show, the two faculty mentors gathered all team members together and dictated a crisp and precise boundary and interface between the two parts of the project.

Each team elected a team leader. We, as faculty mentors, assumed that the team leaders would coordinate the activities between the groups. When directed to discuss and determine the interface, the team leaders were not able to resolve the definition. The lesson learned was that most students do not have the experience to work on hard problems, like developing solid requirements and stable interfaces.

Teamwork: Several team members did not pull their weight during the project planning and execution phase. In fact, one member's lack of activity caused a delay of about four weeks when his part of the design was not delivered on schedule. The lesson learned is that teams need to be taught that critical path tasks should be closely monitored, and that a secondary person should be assigned to back-up the primary person assigned to every task.

Task Focus: As is often the case with even seasoned employees, student team members worked on tasks that were "neat and fun", rather than completing tasks that are a part of the requirements. For example, two students spent the entire summer trying to make a motor controller application work when an off-the-shelf solution was available and already identified by the team before the summer started. The lesson learned is that students again need to adhere to the schedules they established at the beginning of the project.

Inter-team Communications: Communications improved greatly when each team was assigned space in two different labs (which were 50 feet apart), AND the team leads made it a point to visit each other several times weekly. The lesson learned is that communications is greatly enhanced by locality, but the faculty mentors can also encourage frequent communications.

5. Conclusions

Two separate teams worked to complete two parts of a larger senior design project. The end product, a robotic system using stereoscopic cameras for navigation on an autonomous vehicle, was a very complex device that required the students to stretch their minds and abilities. These groups made the mistakes that many teams often make. This senior design project taught the students and the faculty mentors the importance of communications in large team projects. The major lessons learned were that faculty mentors need to pay close attention to their teams and be ready to step in and help guide the team when they are not making sufficient progress. However, the faculty mentor should also allow the students to make some mistakes so that the students can learn from these mistakes.

The senior design faculty member running the senior design course also learned that the senior design students could benefit from more classroom instruction and hands on exercises on teamwork and communications. The instructor also intends on creating a lessons learned database for the students to use during project planning.

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