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The Airborne Environmental Research Observational Camera (AEROCam): A Multispectral Digital Photography System for Remote Sensing

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Abstract

The Airborne Environmental Research Observational Camera (AEROCam) is an aircraft-based remote sensing payload that will collect multispectral image data in four spectral bands and then automatically geo-correct the data to provide a one-meter ground sampling distance. The AEROCam research and development effort was initiated by the Upper Midwest Aerospace Consortium (UMAC), which analyzes satellite imagery for regional farmers, ranchers, and natural resource managers. This sensor represents the first of several data acquisition technologies under development for gathering specific information for UMAC's end users on demand. Design of the AEROCam system is being conducted by a multidisciplinary team of electrical and mechanical engineering undergraduate students at the University of North Dakota (UND). Project management and funding are being provided by the John D. Odegard School of Aerospace Sciences, with the technical management team consisting of faculty and graduate students in the UND School of Engineering & Mines. This research project has provided the undergraduate students with a valuable experiential learning opportunity. Further, the university is benefiting from the project in many ways, from an increased expertise in systems engineering, to a vastly improved research and development infrastructure, to the production of an excellent public relations vehicle.

Keywords: Digital photography. Remote sensing. Systems engineering.

1. Introduction

The Airborne Environmental Research Observational Camera (AEROCam) is a four-band multispectral sensor with extremely high image resolution, designed specifically for flight on University of North Dakota airplanes. Beginning in the summer of 2002, this digital camera will be used to gather remote sensing imagery for precision agriculture and disaster response (*e.g.*, flooding and forest fire) missions. Two colleges at UND, the John D. Odegard School of Aerospace Sciences and the School of Engineering & Mines, are jointly developing the AEROCam sensor. Students and faculty within UND Engineering are responsible for designing, building, and testing the instrument, while funding and program management are provided by UND Aerospace through the NASA-supported Center for People and the Environment (CP&E). This research center is operated by the Upper Midwest Aerospace Consortium

(UMAC), based at the University of North Dakota. The AEROCam sensor was designed, built, and tested for approximately $70,000 in equipment costs, supported by UMAC and the NASA-funded Northern Great Plains Center for People and the Environment. This budget does not include student and faculty stipends. Initially, the sensor will be operated at no cost to its end users.

UND Aerospace maintains and operates a fleet of over 100 small aircraft, which supports the leading four-year aviation program in the country. Through a versatile design methodology, a UND fleet aircraft – specifically one of its modern Piper Arrow airplanes – could be available within a matter of hours to provide digital photography services to customers in the Red River Valley and throughout the Upper Midwest. Given a data request consisting of date/time and latitude/longitude coordinates, digital images will be captured by a pilot navigating over a designated flight path. These images will then be post-processed and delivered via the Internet to end users after the airplane returns to the University of North Dakota.

CP&E and UMAC research interests are centered on remote sensing image analysis for precision agriculture, natural resource management, and disaster response applications, as well as scientific education and outreach. The Upper Midwest Aerospace Consortium already serves a large population of farmers, ranchers, and foresters throughout the region, and UMAC researchers are currently interested in developing customized remote sensing technologies that are truly driven by their end users' needs.

The Upper Midwest is known world-wide for its excellent farming and ranching production, and precision agriculture techniques such as variable rate fertilizer application and strategic grazing can provide even higher yields at a significant cost savings, while simultaneously minimizing environmental impact. Unfortunately, the Upper Midwest is also known for its extremes in weather, including severe blizzards, drought, and windstorms, ultimately resulting in disasters such as flooding, forest fires, and deforestation. Active remote sensing satellites (*e.g.*, Landsat 7) do not currently satisfy the high-resolution, high-frequency revisit, and fast data delivery requirements of precision agriculture and disaster response end users within the Upper Midwest. Thus, UND Aerospace and UND Engineering have started collaborating on the design, build, test, and operation of their own data acquisition technologies to satisfy the specific needs of UMAC's end users. Planned projects include not only AEROCam, an extremely high-resolution (approximately 1-meter) sensor flown near the Earth's surface, but also lower-resolution remote sensing sensors (5-to-10 meters) designed to be flown on the International Space Station as well as orbiting satellites.

From an educational perspective, this experiential learning project has exposed the engineering students to many concepts that simply cannot be introduced in conventional lecture and laboratory courses [2, 3]. From proper documentation techniques and the systems engineering philosophy [1, 4] to teamwork and systems-level integration, students (and faculty) learned valuable lessons in both the technical aspects of engineering and the group dynamics of a large-scale project. The multidisciplinary teaming of electrical and mechanical engineering students and faculty, remote sensing researchers, and aviation support personnel has provided all of the team members with an excellent "real-world" product development experience inside an academic setting.

This paper is organized as follows. Section 2 provides an overview of the entire system, along with the essential end user requirements. The electrical and mechanical subsystems are introduced in Section 3. Multidisciplinary teaming experiences are explored in Section 4, with respect to overall group dynamics and the documentation required for a large-scale project. Finally, a summary of the project experience and future directions for the collaboration between UND Aerospace and UND Engineering is included in Section 5.

2. System Overview

From the perspective of regional farmers and ranchers who use satellite imagery on a daily basis to assist in their operations, the user requirements for remote sensing are relatively few in number:

1. ***High Spatial Resolution.*** A Ground Sample Distance (GSD) of less than 5-meters provides sufficient detail of within-field variability to support virtually all management decisions that can affect crop production.

2. ***Wide Spectral Range.*** Cameras and filters should be selected in the visible (red, green, and blue) and infrared bands because of the wide variety of information that can be extracted from imagery of vegetation across the spectrum.

3. ***High-Frequency Revisits.*** Acquiring remote sensing imagery every 2-3 days during critical stages of a crop's development allows the end user to adapt fertilizer application or grazing patterns to generate the highest possible yields.

4. ***Short Data Latency.*** To be the most beneficial, a remote sensing map-projected product should be delivered directly to the end user who requested it within 24-hours from the time of data acquisition.

Landsat 7 satellite imagery is currently available with coverage over the Upper Midwest, but the 30-meter resolution data with 16-day repeat coverage does not suffice for regional end users. Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors flown on the Terra and Aqua satellites cover the Earth's surface every one or two days, providing 1000-meter resolution data to their customers. Although raw MODIS satellite images are converted to useful map products by UMAC personnel and then delivered in a timely fashion to their end users, the resolution and revisit times are simply not adequate for practitioners of precision agriculture. Optimally, to estimate crop health within a single field, a Ground Sample Distance on the order of 5-meters for each pixel is required, since agricultural equipment is generally around 5-15 meters in width. Furthermore, a revisit interval of less than two days is important, especially during critical periods of the growing season. Since no operating satellite can deliver public domain remote sensing data with these stringent specifications, the best solution is to develop data acquisition sensors for the Upper Midwest that are custom-designed to satisfy these resolution and revisit requirements.

Vegetation analysis requires bandpasses in the visible and near infrared spectral regions. One of the most useful derived map-projected products is the Normalized Difference Vegetative Index (NDVI), which can be calculated from the red and near infrared bands. The targeted farming, ranching, and forestry applications require a 1-meter GSD for the visible and near infrared imagery. Affordable, commercial-off-the-shelf (COTS) area-scan cameras have been acquired that incorporate a focal plane of 1024 x 1024 square detectors. Assuming that the images are taken approximately 1,250 meters above the ground, 17-mm lenses attached to these cameras are capable of producing a 1-meter GSD with a field of view of 160 acres (1/4 section). Likewise, an image of a complete section of land (640 acres) can be captured with a 2-meter GSD from an altitude of 2,500 meters. An NDVI map projection with a 2-meter GSD is shown in Figure 1.

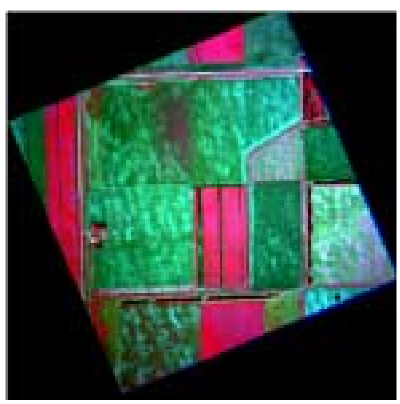

Figure 1 Remote sensing data captured by a multispectral airborne imaging sensor after manual geo-correction of the bands

Traditionally, aerial remote sensing has relied on manual techniques to register the captured image bands using control points selected by the image analyst. By incorporating on-board navigation sensors, these geo-correction parameters can be estimated, and the remote sensing image data can be automatically post-processed after the mission has been completed. As shown in Figure 2, AEROCam consists of the following subsystems:

1. A multispectral digital camera, which includes four area-scan cameras and filters for acquiring red, green, blue, and near infrared (NIR) spectral bands;
2. A differential global positioning system (DGPS) antenna-receiver and an inertial navigation system (INS), to estimate accurate image geo-correction parameters for sensor position (latitude, longitude, and altitude) and attitude (roll, pitch, and yaw);
3. An on-board flight computer, including interface hardware and custom-developed flight software; and
4. An LCD flat panel display with touch-screen capability, to provide operational information to the pilot and/or camera operator as a kneeboard instrument.

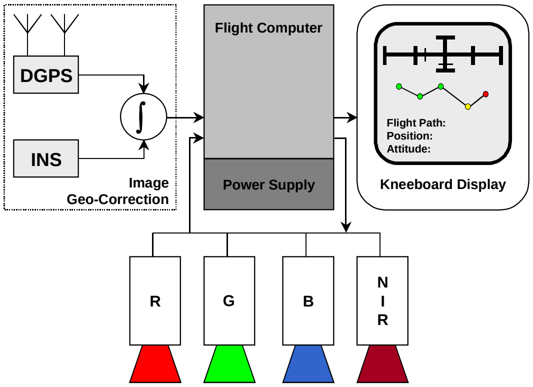

Figure 2 AEROCam system diagram

3. Electrical and Mechanical Subsystems

The AEROCam sensor is fully self-contained; other than physical mounting, there are no connections – power, data, or otherwise – to the on-board aircraft systems. The entire system consists of two avionics racks, which replace the rear seats within a Piper Arrow single-engine airplane; the camera pod, which hangs outside the luggage rack; a GPS antenna mast, which extends above the camera pod; and a flat-panel screen for use by the pilot and/or operator inside the cockpit.

3.1. Electrical subsystem

Four area-scan digital imaging cameras are currently mounted pointing down in the external pod, with each camera containing a lens and a bandpass filter. One of these cameras is shown in Figure 3. A red, green, blue, or near infrared bandpass filter is mounted within each lens housing. An inertial measurement unit, the INS sensor that measures roll, pitch, and yaw, is also installed in the pod with the cameras. A single antenna, capable of receiving both GPS and differential GPS signals, is mounted at the top of a mast extending from the pod. Power and data cables run along the pod arm to the equipment racks, protected by a shield.

Figure 3 Dalsa CA-D4 1024 x 1024 pixel area-scan camera with lens

The avionics racks, depicted in Figure 4, house a ruggedized Pentium 3 flight computer, a removable hard drive for data transfer, a GPS receiver, two DC voltage converters, and the system power supply. AEROCam is powered by one 12-Vdc aircraft battery, which is mounted in a vented plastic case at the bottom of an equipment rack. Four toggle switches at the top of one rack are used to power the system on and off. In addition, all circuits are appropriately protected with circuit breakers. The flight operations crew will use a sunlight-readable flat panel display for system operation.

Figure 4 Avionics racks

3.2. Mechanical subsystem

AEROCam installs into the rear seat and baggage compartment area of a single-engine Piper Arrow airplane, shown with the baggage compartment door open in Figure 5. With the rear seats removed, the avionics racks install into the seat floor mounts. With the baggage door removed, the camera pod extends out the door opening, and is connected to a framework bolted to the baggage tie-down mounts. To reduce the potential for vibration, the GPS antenna mast that extends up from the pod is connected to this door panel, which in turn is connected into the main framework. After installation of the primary framework, the baggage door opening is closed with a custom-built panel. Figure 6 shows the entire AEROCam system, installed within the baggage compartment.

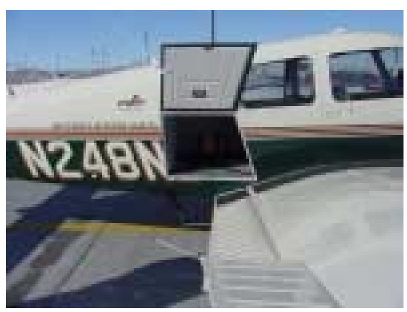

Figure 5 Baggage compartment location on a small Piper aircraft

The Piper Arrow is designed to accommodate one pilot and three passengers, with a maximum weight of 180-lbs each. An additional 200-lbs of luggage is allowed in the baggage compartment with a full load of fuel. This constraint on the overall weight became a real challenge for the mechanical design. Every AEROCam component had to be scrutinized carefully with regards to size and weight. For example, the single 12-Vdc battery currently used within the AEROCam system weighs 65-lbs, but this provides enough power for only a 2-1/2 hour mission. Furthermore, because of the overall weight constraint, the Piper Arrow cannot handle a full fuel load; instead of a 5-hour flight time, flights with only a 4-hour duration can be accommodated with the sensor on-board. In addition to weight considerations, the AEROCam sensor had to be designed to maintain the proper center of gravity for the airplane. Accurate weight and balance measurements were necessary to ensure that the airplane will be safe to fly with the sensor installed.

Figure 6 AEROCam installed into a Piper Arrow single-engine airplane

UND Aviation support personnel were extremely helpful in selecting mechanical and electrical components for AEROCam, as well as acquiring weight and balance measurements with the unit installed. They were also instrumental in creating an efficient installation/deinstallation check-list, since the sensor will not be dedicated to any single airplane. When fully operational, the AEROCam sensor will be activated upon the request of regional farmers, ranchers, foresters, and government agencies, to provide remote sensing data throughout the region served by the Upper Midwest Aerospace Consortium. Scheduling the operations will most likely be challenging, since UND Aviation has a large number of undergraduate and graduate students who need to take private flight lessons and log flight hours. The aviation support staff will become extremely vital to the success of this sensor as more and more data acquisition requests are made by the end users.

4. Multidisciplinary Teaming

Members of the AEROCam system development team include the Principal Investigator and Program Manager from the Upper Midwest Aerospace Consortium; faculty from the departments of electrical and mechanical engineering; undergraduate and graduate students from the departments of electrical and mechanical engineering, either working on master's theses, capstone senior design projects, or for an hourly salary; and support personnel from both aviation and engineering. System development commenced during the 2001 spring semester by a number of undergraduate and graduate engineering students, culminating in a Preliminary Design Review in May 2001. Summer 2001 activities included a mechanical build for the installation of AEROCam into a Piper Arrow; an electrical implementation, which includes support for GPS measurements and four digital cameras; and preliminary discussions with Designated Engineering Representatives (DERs) for a restricted flight certification of this airplane modification by the Federal Aviation Administration. During the 2001-2002 academic year, the system was refined with respect to mechanical installation and flight software, and documents were submitted to the DERs for structural, electrical, and flight certifications.

The team members practiced systems engineering principles to design, build, test, and operate the sensor. The systems engineering philosophy places a premium on documentation and "thinking through" a design before heading into the laboratory [4]. This is a thought process that is often encouraged by professors, but in reality is rarely followed by students. In most undergraduate design projects, the students head into the laboratory with only vague ideas in their minds with regard to their design methodologies. When taking on a large-scale project, a well-planned design is vital, so that when integration finally takes place all of the various subsystems will work together properly. The systems engineering philosophy forces the students to make sure that every subsystem of the project fits together, especially at the interfaces, before parts are ordered and implementation commences.

Large-scale systems integration also rarely takes place in either undergraduate or graduate education. The AEROCam project allowed the students to gain valuable experience that is generally not found in either the on-campus curriculum or through cooperative (co-op) education. While some cooperative education experiences do indeed involve systems integration tasks, the vast majority of co-op students are never exposed in-depth to the methodology and processes involved in this aspect of engineering design. As far as systems integration in undergraduate education is concerned, most design projects are undertaken by small student teams, which greatly limits their scope. By working with a much larger multidisciplinary group, the scale of the project was substantially increased beyond what a typical undergraduate design team could accomplish. Working in a large team also introduced the students and faculty to many aspects of group dynamics, a relatively new experience for the team members.

4.1. Group dynamics

Dealing with group dynamics helps students to polish their “soft skills,” which are vitally important in today’s business world. Soft skills, including oral, written, and interpersonal communications, are often the most important skills that a person must possess in order to advance one’s career. Working in large groups as a part of the undergraduate and graduate curricula provides students with a chance to hone their people skills, which generally occurs only in an industrial cooperative education setting. From weekly face-to-face progress meetings, to teleconferences with the DERs, to dealing with the media, the students learned from experience how they must work together as a team to accomplish their goal of getting customized remote sensing data into the hands of precision farmers, ranchers, and foresters.

Group design projects in the undergraduate curriculum usually consist of small numbers of students working together, generally with no more than two-to-four students in any single group. Typically, these groups are either handpicked by the professors or self-selected among friends and study partners. Although students do learn some teamwork skills from these interactions, they lack the experience of working in larger groups, as well as working with students with whom they may not socialize. The AEROCam project taught the students important lessons in teamwork and its necessity in the successful completion of large-scale engineering projects with short timelines.

Team members had significantly more responsibility and accountability placed on their shoulders than they had ever encountered previously in an engineering project. They were responsible for making decisions on everything from the user requirements and the components used in each subsystem to the FAA certification process and how to begin mission operations. Students learned how to make informed group decisions and to deal with the ramifications of these decisions. Since each student was responsible for a major portion of a subsystem, he or she also learned how to depend on others to complete the mission. If only one person did not fulfill his/her tasks, the mission would be unsuccessful, as opposed to most undergraduate design projects in which one or two students usually do the majority of the work and the others just “get by.” Part of the interdependence of the team members was grounded in the integration and test deadlines. Delaying one test of a subsystem directly impacted everyone else’s schedules. Students were also responsible for adhering to the cost, power, size, and weight budgets set forth in the design and documentation phase of the project.

Because the students had not only full class loads but also outside jobs, there were very few common work hours among the team members. The only time that the whole group was assembled was during the weekly progress meetings, which made these sessions the most convenient times to discuss problems with the other team members. In contrast, a great deal can be accomplished by the team during the summer months. The faculty mentors were hired as research fellows to work full-time on the project during the summer, while students were hired as research assistants on an hourly salary. During the school year, however, it became much more difficult to accomplish tasks in a timely manner, because of the number of courses taught by the faculty and the number of courses taken by the undergraduate and graduate student team members. Typically, master’s-level students were hired as half-time graduate research assistants during the academic year, and they could accomplish a great deal because of their dedication to completing their theses. Several undergraduates were hired as research assistants for approximately 10-hours per week during the school year, so that they could accomplish the necessary tasks to prepare the sensor for FAA certification and mission operations. Students involved in the project through the capstone senior design course sequence were not as dependable as the research assistants employed for the project, but they did accomplish enough tasks for their course grades to contribute to the team effort.

5. Summary and Future Directions

The AEROCam sensor has provided a number of opportunities for engineering students at the University of North Dakota to conduct real-world R&D within an academic environment. In the process of enhancing their technical skills, they were also forced to practice their oral, written, and interpersonal communication skills. Moreover, the students, faculty, and staff learned how to work together as a team to accomplish a common goal. To design, build and test a instrument of this complexity at such a low cost compared to a commercial venture, the contribution of every team member becomes critically important.

A plethora of research and development tasks related to AEROCam await the engineering students over the next several years, including (but certainly not limited to):

- Geometric and radiometric camera calibration;
- Software modifications for ground-based automated image geo-correction;
- Conversion of the raw data into a useful map product in the GeoTIFF image format, which can be imported into most geographic information system (GIS) software packages;
- Implementation and test of the DGPS/INS Kalman estimation algorithm, to improve the accuracy of position and attitude measurements;
- Examination of the possibility of interfacing to the aircraft power system for longer flights, rather than using an independent (and very heavy) battery to power the sensor;
- Investigation of using a carrier-phase DGPS for highly-accurate position measurements;
- Image analysis of the remote sensing data and precision agriculture data distribution via the Internet;
- Addition of a long-wave infrared (LWIR) camera for thermal imaging applications; and
- Calculation of cost savings provided to farmers and ranchers from the utilization of this service.

The UND Aerospace/Engineering partnership will continue even after the AEROCam sensor is completely operational during Upper Midwest growing seasons. Plans are in the works to design, build, test, and operate both airborne sensors as well as remote sensing instruments which orbit the Earth. Future projects which have either been discussed or are currently being pursued in earnest include: (1) an airborne hyperspectral sensor; (2) operation of the Agricultural Camera (AgCam), a two-band sensor placed within the International Space Station's Window Observational Research Facility (WORF); (3) the development of a satellite ground station to gather MODIS data and remote sensing imagery from other satellites; and (4) development of a university-based remote sensing orbiting satellite, with the orbit tailored to the Upper Midwest growing season.

6. Acknowledgments

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