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UTILIZING UAV PAYLOAD DESIGN BY UNDERGRADUATE RESEARCHERS FOR EDUCATIONAL AND RESEARCH DEVELOPMENT

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ABSTRACT

An undergraduate team consisting of mechanical and electrical engineering students at the University of North Dakota developed an electro-optical and un-cooled thermal infrared digital imaging remote sensing payload for an Unmanned Aerial Vehicle (UAV). The first iteration of the payload design began in the fall of 2005 and the inaugural flight tests took place at Camp Ripley, Minnesota, a National Guard facility, in the fall of 2006 with a corporate partner. The second iteration design with increased performance in object tracking and data processing is expected to fly in the summer of 2007.

Payload development for integration into a UAV is a process that is not currently well defined by industrial practices or regulated by government. These processes are a significant part of the research being conducted in order to define the “best practices.” The emerging field of UAVs generates tremendous interest and serves to attract quality students into the research. As with many emerging technologies there are many new exciting developments, however, the fundamentals taught in core courses are still critical to the process and serve as the basis of the system. In this manner, the program stimulates innovative design while maintaining a solid connection to undergraduate courses and illustrates the importance of advanced courses. The payload development was guided by off-the-shelf components and software using a systems engineering methodology throughout the project. Many of the design and payload flight constraints were based on external factors, such as difficulties with access to airspace, weather-related delays, and ITAR restrictions on hardware.

Overall, the research project continues to be a tremendous experiential learning activity for mechanical and electrical engineering students, as well as for the faculty members. The process has been extremely successful in enhancing the expertise in systems engineering and design in the students and developing the UAV payload design knowledge base and necessary infrastructure at the university.

INTRODUCTION

As the Unmanned Aircraft System (UAS) community continues to expand at an exponential rate, the need to develop Unmanned Aerial Vehicle (UAV) payloads follows. This exciting, innovative development poses several challenges for the university community to be an active partner. The thermal-optical imaging payload developed is the culmination of a two year-long project at the University of North Dakota (UND). The imaging system was designed and built by mechanical and electrical engineering undergraduates enrolled in the UND School of Engineering & Mines, and was tested for the first time in Lockheed Martin’s Sky Spirit experimental UAS in the fall of 2006.

The mission of the UND payload design project is to research, develop, test, and demonstrate a complete UAS imaging system capable of capturing real-time electro-optical

(EO) and thermal infrared (IR) image data, inertial measurement unit (IMU) orientation information, and GPS position data that may be used in a small UAS for a wide array of civilian applications, including wildfire fighting, disaster response, and precision agriculture. The imaging system uses state-of-the-art cameras, as well as position and orientation sensors to provide the highest possible level of data accuracy with relatively small size and power characteristics. To accomplish these objectives, an embedded computer, a wireless transceiver, and active command and control functions via a remote ground control station are used.

The project attracted many outstanding students and serves as an excellent recruitment tool to get students interested in a technically challenging project. To date, 12 undergraduate students and 3 graduate students in mechanical and electrical engineering have been part of the payload design team. The project incorporates many new innovative and developing technologies, but reinforces the fundamentals of a general engineering education. As UAS become a bigger player in the world of aviation, the students involved in this project will have many of the tools necessary to be an integral part of the development.

PROJECT OVERVIEW

The team at the University of North Dakota began the first UAV payload during the 2005 academic year. This payload was completed and flown during the fall of 2006. Shown in Fig. 1 is part of the team that worked on the project.

Fig. 1. The UAV payload during final construction along with a portion of the design team.

The first flight of the payload was flown in restricted airspace above Camp Ripley, near Little Falls, MN. Both electro-optical and infrared images were obtained during the flight. Shown in Fig. 2 and 3 are example images taken during the flight. In each case, different aspects of the imagery are more pronounced. In the EO imagery things such as painted indicators and colors are easily observed, whereas, in the IR imagery the cool targets are clearly seen. The IR imagery also allows for night-time use.

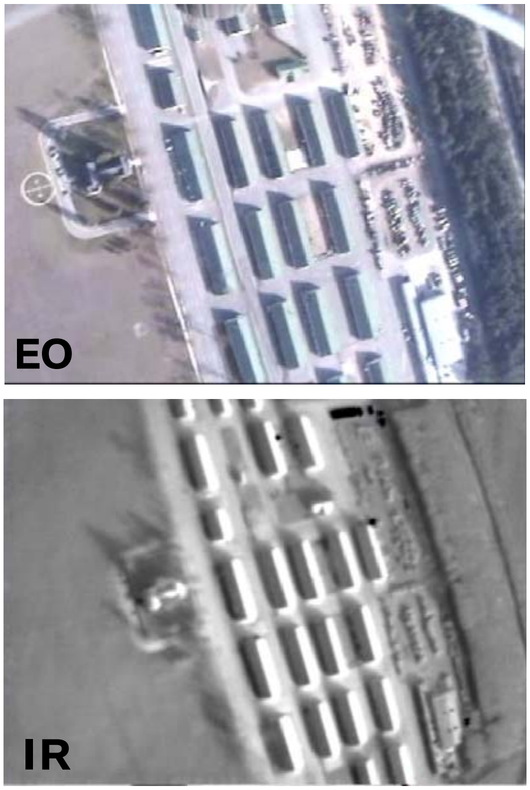

Fig. 2. Example images taken during the inaugural flight. Top image is in electro-optical and the bottom image is in infrared.

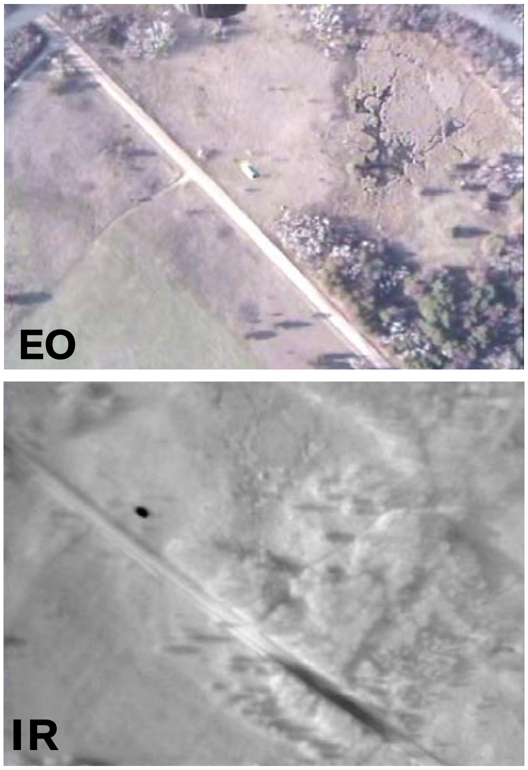

Fig. 3. Example images taken during the inaugural flight. Top image is in electro-optical and the bottom image is in infrared.

PAYLOAD DEVELOPMENT

To develop the complex system that constitutes an UAV payload a systems engineering approach is used. Each specific payload has unique components that need to be integrated into a functional system. First, the primary objectives of the payload are developed. From here, an extensive trade study is conducted to identify likely components for implementation. The use of commercial off-the-shelf (COTS) components is encouraged, especially if they have flight heritage. This is the most efficient use of resources, both from a personnel and expense perspective. Each of the development teams is tasked with developing their own sub-systems and periodic, nominally weekly, meetings are held to orchestrate integration. These also serve to obtain updates and encourage ongoing progress. Progress reports are provided and integration issues are discussed at the meetings. In this manner, the entire team is kept abreast of the progress and appropriate action items are assigned.

Using this approach, the complete imaging system was constructed that includes three primary subsystems; the payload subsystem, the ground control station subsystem, and the software subsystem. The payload subsystem is comprised of both an EO and an uncooled thermal IR image sensors, an IMU to determine orientation information, a GPS receiver for sampling position data, a PC/104+ embedded computer system for data processing and control functions, and a 2.4 GHz wireless ethernet transceiver to communicate wirelessly in near real-time. Figure 4 shows the sensor payload subsystem. The overall weight of the payload is 15 lbs and has overall dimensions of 23-in. × 8-in. × 6-in.

The mobile ground control station subsystem is comprised of a laptop computer with an additional flat screen monitor for multiple program viewing, a wireless ethernet transceiver, and a ruggedized carrying case for the entire system. The function of the mobile ground control station is to command and control the sensor payload, monitor flight information, and receive EO and IR image data in near real-time, all via the 2.4 GHz wireless datalink. A ruggedized carrying case is used to safely house all of the components used in the imaging system while in transit. Figure 5 shows an example mobile ground control station screen.

The software subsystem is comprised of several different open source computer programs and two primary Operating Systems (OS). The sensor payload CPU uses the SuSE Linux OS to enable more efficient real-time operating applications in a less volatile environment. The ground station uses Windows XP since many off-the-shelf development tools are most compatible with this platform. The two systems are interfaced via Putty, a program that enables communication between Linux and Windows. Several open source programs are run on the ground station, including Video Logic Control (VLC) for viewing the EO and IR image sensor data, Flight Gear UAS simulation software for orientation and navigation information, NASA's World Wind three-dimensional mapping software to indicate GPS location, and batch file executables to operate command and control functions.

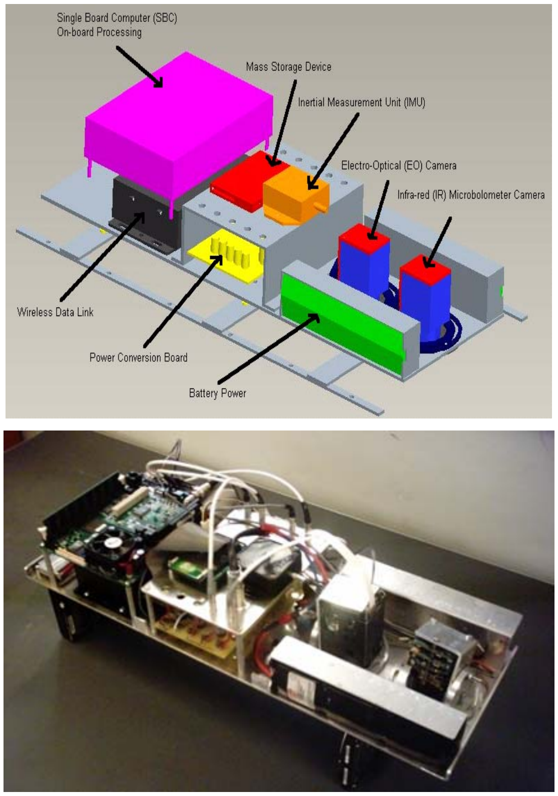

Fig. 4. The EO/IR imaging payload in CAD format (upper)and in a digital image (lower).

Fig. 5. The ground control station user interface.

One of the unique challenges in this development is the lack of established guidelines from industry and/or governmental agencies. UAS are experiencing tremendous growth and the regulatory guidelines are not well established. However, the UND team is helping to define the "best practices" for the industry. The mechanical and electrical engineering programs at UND have had extensive experience in developing manned aerial and space payloads [1,2]. These have been overseen by governmental regulatory agencies, such as the Federal Aviation Agency (FAA) and NASA. These experiences have served us well to create the appropriate guidelines for the unmanned payloads. Several key design considerations have been established including the use of mil-spec hardware, nonflammable and non-off-gassing cables, electro-magnetic interference (EMI), aerodynamic considerations, cooling issues, and weight and balance of the aircraft. To satisfy these requirements a completely self contained system has been produced, which includes power and communication abilities.

The ability to effectively work and grow a multidisciplinary research team to deal with the many technical challenges an aerospace related project is essential. UND and others have had success in workforce development in the UAS field [3-7]. The work on UAS payloads is only one area of interest, and many other areas are critical in the continued enhancement of the complex developing UAS industry.

The mechanical system design is comprised of mostly custom components constructed in-house. To conserve space multiple layers are used by elevating several of the electrical components above a base plate, including the IMU, solid-state hard drive, and Lemo plugs, which are high-grade EMI shielded connectors commonly used in aircraft systems. A custom aluminum bracket was constructed by students to allow for manual pointing capabilities of the infrared and electro-optical cameras. The bracket design allows the cameras to be pointed up to 30 degrees off-nadir and rotated 360 degrees around the nadir axis. Currently, the bracket must be manually configured to the appropriate angle before the sensor payload is flown. The two cameras and their positioning brackets are shown in Fig. 6.

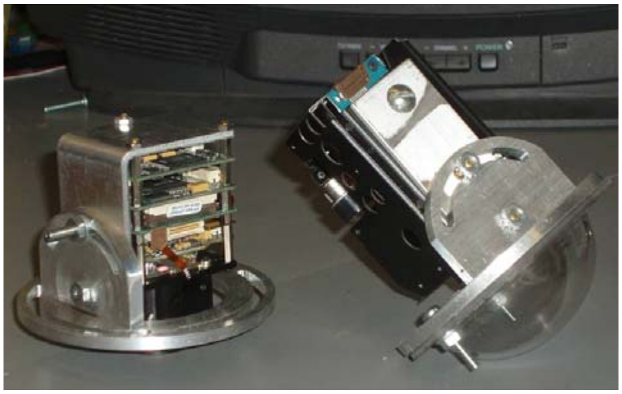

Fig. 6. Custom camera brackets to allow manual pointing.

Another mechanical system design that was addressed was vibration isolation. Due to the high-vibration environment exhibited on almost all small UAS airframes, a critical mechanical design consideration involved protecting the sensor payload from damage due to this vibration. To resolve this issue, commercial-off-the-shelf (COTS) vibration isolators were purchased from Lord, Inc., which are attached to the sensor payload mounting frame. This system provides passive broad-band isolation that reduces the effective transmissibility of vibrations, as well as improving image data and orientation information. Figure 7 shows an image of the mounting frame, which is made out of 1/8th inch aluminum on the base and uses balsa wood and a Plexiglas surface to mimic the contour of the fuselage. The design specifications were defined by a Payload Integration Manual (PIM) provided to the UND imaging system design team by the Lockheed Martin Corporation. The PIM listed all of the necessary interface specifications for the payload bay in the Sky Spirit UAS.

Figure 7. Payload mounting interface bracket.

The electrical system design is a compilation of several different electrical components that each performs a specific function. All of the electrical components are either COTS devices or are custom designs produced by electrical engineering students. The retrieval, formatting, and processing of the sensor data is performed on the payload by using a VersaLogic PC/104+ Single Board Computer (SBC). The SBC also has a Sensoray frame grabber attachment, in order to retrieve the digital signals output by both the EO and IR cameras. The IR camera is a BAE Systems microbolometer-based, uncooled 320 × 240 infrared sensor that is extremely small and lightweight. The EO camera used in the sensor payload subsystem is the Sony Block Camera. This camera is used for visible imaging applications and has 26× optical zoom capability. The Garmin 15H GPS receiver is used in the payload to determine location information. This Wide Area Augmentation System (WAAS) enabled device is capable of three-meter accuracy and can use up to 12 satellites for more precise positioning information. Orientation information is received via the MicroStrain IMU, a tri-axis orientation sensor that uses gyroscopes, magnetometers, and accelerometers to determine roll, pitch, and yaw. The orientation and position data may be especially useful for post-processing image data. A FastLinc 2.4 GHz wireless ethernet modem is used on the sensor payload in order to communicate wirelessly with the ground control station. For power distribution, a custom Power Control Board (PCB) was designed that uses Vicor DC-DC converters. The sensor payload is a completely enclosed unit, and thus operates using two Lithium Polymer (LiPo) batteries.

A Mesa CompactFlash card reader is used with a Transcend 8GB solid-state hard drive to run the Linux OS and store sensor data. A solid-state hard drive is used because of its resilience to high-vibration environments. Another major design consideration involved electrical cabling. The many connections made between COTS devices necessitated the construction of custom cables. Also, all of the high-grade Lemo plugs were used to interface with the power distribution board, which required further cable construction. To reduce EMI interference created by these custom cables, precautions were taken by using shielded cable throughout most of the design, grounding every device to the base plate, and using shielded plugs. The total power budget is under 40 W and is capable of operation for over 4 hours.

STUDENT INVOLVEMENT

Throughout the project it has truly been a multidisciplinary effort. The primary contributors have been in mechanical and electrical engineering. Both of these disciplines are crucial to successful completion of an operational system. The teams to date have been composed primarily of capstone senior design teams and undergraduate hourly employees. Today the project is expanding and the use of graduate students is growing. To this end, the scope of project must be appropriate to the level of expertise and the time available. However, it must be noted that undergraduate students can make remarkable progress when provided with appropriate resources. This is especially true during the summer months when a more concentrated effort can be made.

Students are recruited through in-class observations and a general enthusiasm for aerospace related projects. UAS has been a hot topic in the news recently, and this has assisted in bringing interest into the research area. The general awareness is also increased due the Grand Forks Air Force base and its upcoming UAS mission. In addition, the John D. Odegard School of Aerospace Science at UND is world renowned aviation school. The UAS payload development efforts have been in close collaboration with the aerospace school. The design and construction of the payloads are the primary responsibility of the engineering school and the FAA regulatory and training of UAS pilots lies within the aerospace school. In this manner, the work of each entity is complementary and creates a full functioning team from which to operate a UAS.

The students involved have been encouraged to present their findings through many venues. This dissemination of information has been through papers and conference presentations. These include the AIAA Infotech@Aerospace and the student AIAA student conference in Colorado Springs, CO [8,9]. Both the writing of papers and attending conferences have offered these undergraduate students a unique opportunity to be involved. In many cases, the students involved with this project are associating with graduate students at these conferences. This exposure also leads to a greater sense of involvement and true ownership.

The research activities support the tools developed in several core engineering courses. From early general courses in statics, dynamics, circuit analysis, and mechanics of materials to core courses in mechanical and electrical engineering. In mechanical engineering other key courses include machine design, measurement laboratories, fluid mechanics, thermodynamics, and senior capstone design. In electrical engineering, applicable courses include electromagnetic fields and waves, digital electronics, computer programming, and capstone design. In the core undergraduate courses the material studied has direct application to the project and is essential for the students to apply this knowledge to complete the tasks required by the design. The activities also support graduate course curriculum that are in part structured around the research activity. Often undergraduate students opt to take graduate level courses that are meaningful to the research work they are conducting. Graduate courses directly supported by the research include advanced vibrations and dynamics, finite element analysis, advanced thermodynamics and fluids, robotics, and avionics, to name a few. Often, graduate course projects are required and students are encouraged to incorporate their research topics into the course curriculum. Due to the broad breadth of UAS payload development work, meaningful projects that fit both the needs of the course and research area are easily found. The UAS project also generated interesting practical examples where the topics from within the course can be used to solve these actual situations.

During the capstone design experience, both disciplines work together in a collaborative manner. At UND this is accomplished by teaming all the students together, although each discipline has its own capstone course. Within the current programs slightly different objectives are in each of the capstone design sequences. It is difficult to have a single capstone course that would include both disciplines due to the fact that some projects lend themselves well to cross disciplinary activity while others are not well suited for this purpose. The historical separation is also well entrenched within the curriculum and many faculty. However, at UND the programs are relatively small and have the flexibility to adapt to innovative changes. Both mechanical and electrical engineering have their own course curriculums and the students in each must meet the respective requirements. Differences include the frequency and magnitude of progress reports and updates. In each case it is the responsibility of the students in the corresponding discipline to lead the efforts and make sure these are accomplished. This is where an equal distribution of students from ME and EE works well. Otherwise, if a majority of one type over the other exists there is a natural tendency to emphasis the needs of the dominate group. At the end of the semester one final paper and presentation are given by the entire team. Representatives from each of the departments grade the papers and are present to evaluate the presentation. The final grades are assigned by the student’s home department, but evaluations are requested from all the parties and used in the grading process. The student credit hours are therefore assigned to the respective departments. UND does encourage these type of collaborations and the efforts are recognized within the departments and the school as important, but unfortunately not in the same manner as more conventional projects where a single investigator receives the credit. These issues are undergoing changes to properly assign credit and indirect monies to the contributing personnel to further promote these cooperative activities.

UAV PROJECT HAZARDS

During the development of the project, UND has formed collaborations with corporations. This was essential in this case, since the development of an airframe and a flight controller were not included. A decision was made to concentrate on payload development and not airframe development. There are a number of excellent airframe developers and working with them to design appropriate missions has been a rewarding process. In order to have an effective partnership between a university and a company, both the academic and corporate goals must be fulfilled. The major issues in these partnerships are the choice of appropriate projects, the use of capstone design courses, opportunities for internal and external funding, management strategies, and dealing with intellectual property ownership rights [10].

The most crucial component of successful industry/university collaboration is the choice of project. It must meet the educational needs of the academic department while also being of significant interest to the industrial partner. In most cases, it is appropriate that the project emanates from a current or anticipated problem faced by the company and/or university. Furthermore, the project should be both high in risk and high in reward, but not time critical to the industrial partner. In engineering programs, the project goals should support a majority of the ABET outcomes for continued accreditation. In this project, the most strongly supported outcomes include the abilities to apply knowledge of mathematics, science, and engineering; to design and conduct experiments; to design a system, component, or process to meet desired goals; to function on multi-disciplinary teams; to identify, formulate, and solve engineering problems; to communicate effectively; and to use the techniques, skills, and modern engineering tools necessary for engineering practice. A key factor that must be maintained is that the university is not just a consulting firm providing work-for-hire. It is an educational entity first and foremost, which places serious limitations on student and faculty time due to other teaching, research, and service commitments. Often times, an efficient means to carry the project out is through the capstone design sequence.

The UAV payload development research has strengthened the research capabilities of UND and has helped establish a successful and productive research environment that is well-positioned to seek out external federal, state, and local government funding opportunities. This has been established through strategic purchases of appropriate equipment in the research labs with university funds and corporate sponsorship. This history of cooperative research with industry also illustrates the complementary activities that are helpful and/or essential to attract additional funding.

Effective project management strategies have been developed to maintain progress and organize the complex system with the relatively large number of participants. These strategies are conducted in cooperation with the Senior Design classes. The Senior Design teams typically have weekly one-hour meetings and periodic teleconferences and plant visits to corporate facilities.

Intellectual property ownership often becomes a significant issue whenever university and industry cooperative research is conducted. If there is the potential for significant scientific discovery and economic impact, these issues must be discussed with appropriate agreements negotiated up-front. Of course, it is extremely challenging to craft a joint intellectual property ownership rights agreement before any collaborative research and development has taken place. Academic freedom to publish is a critical aspect of student and faculty development within academia, while confidentiality and intellectual property protection are essential to the industrial partner. These fundamental differences in culture – “publish or perish” in academia and “protect or perish” in industry – are where the difficulties lie at the industry/university interface. Therefore, a high priority review process is needed that can approve the dissemination of material into print or electronic media in a timely fashion. Other significant issues include naming the assignee to an invention, applying for patents and trademarks, costs associated with filing, prosecuting, issuing, and maintaining patents, commercializing inventions, and negotiating an exclusive or nonexclusive license with the industrial partner that has a fair royalty revenue stream back to the university. If federal funding was utilized to conduct the research, the cooperative research agreement is also subject to the rights of the federal government set out in chapter 18 of Title 35 of the United States Code (i.e., the Bayh-Dole Act), section 401 of title 37 of the Code of Federal Regulations (i.e., the codification of the Bayh-Dole Act), and section 650.4(a) of title 45 of the Code of Federal Regulations (i.e., the National Science Foundation’s patent rights clause), with the rights of the parties governed by the laws of the state where the research was carried out. Additionally, the federal government holds a nonexclusive, royalty-free license to any invention created by its support, and this can truly complicate matters for the industrial partner. These agreements must be dealt with at the university level and the appropriate non-disclosure documents put in place.

Several unique challenges arise while working with UAV payloads. The first and foremost is the ability to operate in the National Airspace System (NAS). The FAA regulates the airspace and the guidelines for operating UAS in the NAS are not established. Therefore, it is very difficult to gain permission to fly. A select few airframes have been granted special permission to operate, but it is a very select group. The other option is to utilize restricted airspace where there is no other air traffic. These areas are often associated with military installations and access can be problematic and/or expensive. This is especially true as more and more UAS developers are trying to use this limited resource. Once an appropriate airspace for operation is found, the weather can produce long unanticipated delays. UAS operate only on clear days with limited wind. Typically, UAS are not well suited to handle cross winds, so this can be an obstacle with limited runway directions. UAS pilots are another limited resource since there is currently no civilian program that certifies an operator of a UAS.

The airspace and UAS pilot training issues are both being resolved at UND. Recently, the university has been granted the use of some restricted airspace relatively close by. The training problem is being tackled by the aerospace school, which has been training traditional manned aircraft pilots for years. It is expected that a new UAS program will be available soon and the FAA certification will be forthcoming.

ITAR restrictions also apply if international students are involved with the payload. Several of the components are restricted due to security concerns, therefore certain components, such as the IR camera, that are accessible by students must be restricted.

FACILITY DEVELOPMENT

The facilities at a traditional engineering school provide the core ingredients to enter into the production of a UAS payloads. However, as in the case of any fabrication efforts, additional demands on current resources are increased and new resources are often required. The access of a well equipped machine shop with trained personnel is essential. With little commercially available components, most mechanical structures are built in-house. This often leads to unforeseen problems due to the relatively small size of the produced parts, as compared to the majority of traditional machining operations conducted at a university machining center. This reduction in size is mandated due to small size of the airframes and the limited weight they can carry. Along with this, a well appointed electronics fabrication facility is needed along with an experienced technician. While students are remarkably talented in much of the design, often times an experienced technician is irreplaceable in the skill sets they bring. Other specialty equipment that are useful include mechanical vibration equipment to test the workmanship and the susceptibility of the payload to vibration and EMI testing equipment to measure the radiated emissions from the payload to determine if it will interfere with the aircraft.

Through the collaborations with corporate partners specialty equipment can sometimes be accessed at their facilities. One such testing opportunity was provided at the Lockheed Martin facility in Eagan, MN, as shown in Fig. 8. The results from the test without any EMI shielding indicated levels above the acceptable range. In anticipation of this, a complete enclosure had been built, as shown in Fig. 9, to contain the radiation. Through several iterations the emissions were reduced to acceptable levels and the payload was deemed acceptable for integration.

The last piece of the facility issue to deal with is space, both for fabrication and operation. The need for research space is an ongoing struggle for most campuses and significant space is required for the establishment of a lab. In our case, the primary design and assembly area is approximately 500 square feet. This includes test and work benches along with 4 computer workstations. The airspace to operate in is the most challenging aspects of the entire endeavor. This is true for all UAS efforts and the FAA is addressing the issue to come to a system of regulations to ensure the safety of the airspace for all who use it.

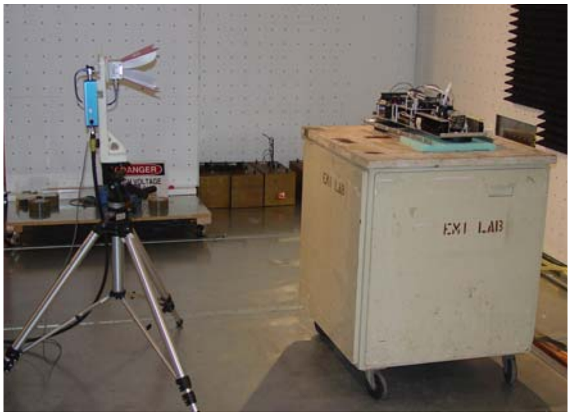

Fig. 8. EMI test setup performed at Lockheed Martin.

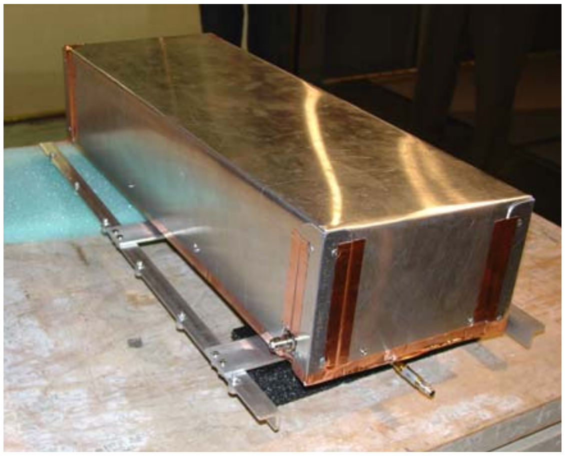

Fig. 9. Aluminum EMI enclosure for the sensor payload.

CONCLUSIONS

To date, the undergraduate research team has accomplished significant advances in payload development. The EO/IR payload was the first UAS payload developed and it has been flown successfully. This first iteration has defined many best practices that have developed through trial and error and significant interaction with corporate partners. While the efforts are implemented in a new environment, they rely heavily on the fundamentals taught in the traditional classroom setting. The illustration and implementation of these principles through a systems engineering approach enforce and much more fully develop a greater understanding in the students. The use of COTS components for a specialty application is encouraged, much as in many commercial endeavors. While UAS payloads have unique challenges, the overall project lends itself well for an exceptional experiential learning experience that is beneficial in many fields.

The team of mechanical and electrical engineering personnel has achieved a high level of success and is currently undertaking additional payload developments that will provide advanced capabilities. This is accomplished through an ongoing learning process that utilizes the rapidly developing technologies that become available. The lessons learned and the great enthusiasm help make this project a truly rewarding program.

ACKNOWLEDGMENTS

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