Development of an Autonomous Aerial Reconnaissance System

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Abstract

A multidisciplinary team of undergraduate students from LeTourneau University has developed an autonomous aerial reconnaissance system to participate in the International Aerial Robotics Competition. The current system has been designed with the goal of demonstrating autonomous flight. Additional capabilities will be integrated in the future, as part of the multi-year project objectives. This paper introduces the International Aerial Robotics Competition, provides an overview of the project, and describes the mechanical, electrical, and software components of the autonomous flight control system.

1 INTRODUCTION

LeTourneau University is competing for the first time in the 2004 International Aerial Robotics Competition (IARC). The team multidisciplinary of undergraduate students from LeTourneau University, known as the Phoenix Project, has focused its efforts on achieving basic autonomous flight capabilities during the first year of a multi-year endeavor.

The IARC requires three distinct levels of autonomous robotic behavior [1]. The first level involves the demonstration of autonomous flight along a 3 km path by means of waypoint navigation. The second level requires that a specific target building be identified using visual pattern recognition techniques. In addition to recognizing the correct target building, open entryways leading into the building, such as windows and doors, must be identified. The third level of robotic behavior requires entering the target building and transmitting reconnaissance data in image or video format from inside the building to the competition judges. After the three levels of autonomous robotic behavior are achieved, they must be demonstrated consecutively in fifteen minutes or less to accomplish the IARC mission objectives.

The Phoenix Project has focused its first year of design work on demonstrating Level 1 behavior, while concurrently taking into account the future functionality required to meet Levels 2, 3, and 4. The design of the main aerial vehicle, the onboard electronics, and the control system software allows for expansion and flexibility. Even though the current design does not include a sub-vehicle, telemetry, and visual pattern recognition capabilities, these subsystems will be integrated in upcoming years. Weight and power constraints for additional subsystems have been considered, ensuring that upgrades will be implemented seamlessly.

A helicopter was selected as the primary flight platform because of its capability to perform all levels of competition required by the IARC. A helicopter's extreme maneuverability allows it to adapt to the type of flight necessary for accomplishing a large variety of missions. A Bergen Industrial Twin helicopter was purchased and outfitted with an array of electronics. The system block diagram shown in Figure 1 provides an overview of the electronics used in the current control system, as well as insight into future design upgrades.

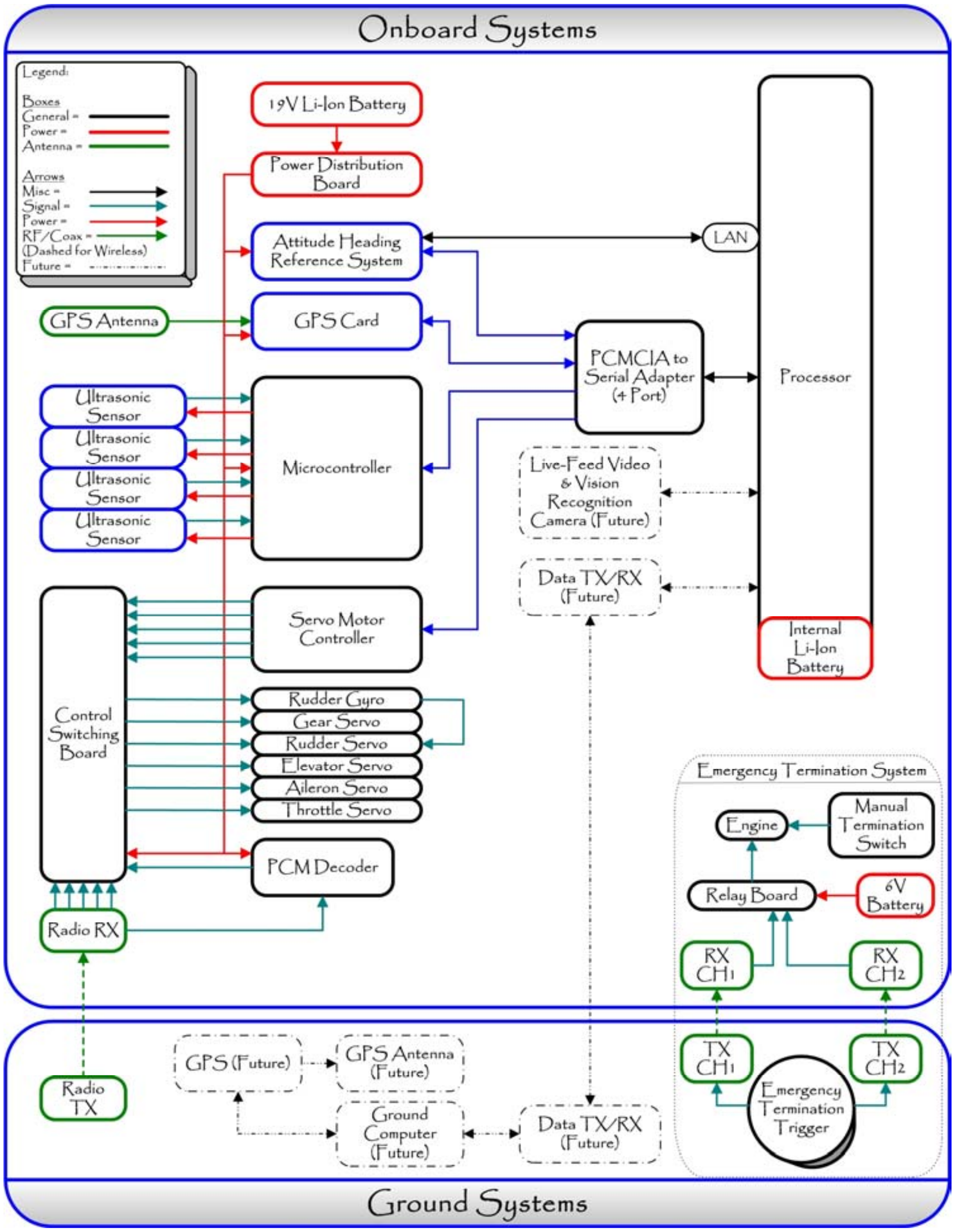

Figure 1. Control System Electronics Diagram

The electronics are divided into three general areas: onboard systems, ground systems, and an independent emergency termination system. The onboard systems include all of the components required for autonomous flight – a processor, an Attitude and Heading Reference System (AHRS), obstacle avoidance sensors, and GPS navigation equipment, as well as power and control switching hardware. The ground systems are comprised of a radio controller, a differential GPS receiver, and a future ground-based computer and transmission system for receiving live-feed video and telemetry. The emergency termination system contains both onboard and ground-based hardware, including transmitters, receivers, and relay circuitry.

Flight control can be readily interchanged between manual radio-controlled flight and autonomous flight by switching the servo input signals between the radio receiver and computer. This allows a human pilot to regain control at any time during autonomous flight. The emergency termination system is a required safety feature that will be used as a last resort to ground the engine ignition spark and halt forward flight in the event that the vehicle becomes a danger to spectators.

2 AIR VEHICLE

2.1 Propulsion and Lift System

The primary flight platform used is a Bergen Industrial Twin helicopter (Figure 2). A helicopter was selected over other types of platforms based on its superior capability to accomplish all levels of the competition. Utilizing an 8 horsepower, twin cylinder gasoline engine and 1.6 meter main rotor diameter, this helicopter is capable of lifting a useful payload of approximately 25 lbs. Its power, payload capacity, and proven stability led to the selection of the Twin for the primary flight platform. Due to the blade length required to achieve the desired lift capability, this helicopter will not fit through the competition-specified one meter square opening in the target building. Therefore, in order to enter the building for the third level of competition, an aerial sub-vehicle will be designed and implemented in future years to meet this need.

In order to protect the onboard systems and maintain the structural integrity of the helicopter frame, a carbon fiber enclosure houses a majority of the electronics. The antennas, the obstacle avoidance sensors, and the AHRS are mounted externally on the enclosure. The obstacle avoidance sensors are mounted with damping gel and silicone grommets to reduce the vibration transmitted through the enclosure from the engine. The orientation of the sensors is designed so that one sensor faces forward, one downward, and one to each side. The AHRS is mounted on a vibration damping gel to the top of the enclosure behind the main helicopter frame.

The carbon fiber enclosure itself is integrated as a stress-bearing frame component and is mounted to the underside of the helicopter between the frame and landing skids. Extending from the rear portion of the enclosure is a pair of struts, which support the tail boom for proper rudder control. Carbon fiber was used to fabricate the enclosure to minimize its weight while maintaining the strength and rigidity necessary to protect the electronics and support the vehicle when landing. Within the enclosure lie several baffles which divide the enclosure into two main sections. The purpose of this division is twofold. First, the baffles act as bulkheads in the event of a hard landing by preventing the heavier components from shifting and crushing the more fragile components. Second, the baffles allow the engine's pull-start mechanism to descend partially into the enclosure without contacting any components.

Figure 2. Bergen Industrial Twin with Carbon Fiber Electronics Enclosure

2.2 Guidance, Navigation, and Control

Flight Control Software

The flight control software has three main functions: stabilization, obstacle avoidance, and navigation, as shown in Figure 3. The flight control software communicates with the sensor drivers to retrieve data from the various sensors onboard the helicopter, and outputs control instructions to the servo motor controller, which then encodes them into signals the servos can use. Capabilities such as visual pattern recognition and the wireless data-link to the ground station computer will be part of the functionality developed in the future. The flight control program runs on the helicopter's onboard computer in a Linux operating system.

The three functions performed by the flight control program have different priority levels, stabilization being the highest and navigation the lowest. Whenever the helicopter becomes unstable, the control system first resumes a stable hover, and then continues navigating to the next waypoint. Likewise, if the control system detects an obstacle in the flight path, it immediately puts the helicopter into an evasive flight pattern to avoid the object. Then it recalculates the trajectory to the next waypoint and resumes normal forward flight.

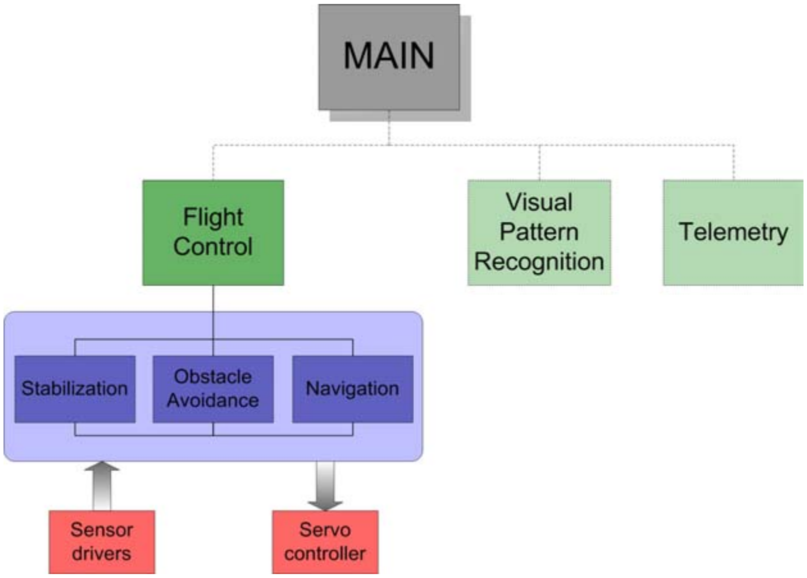

Figure 3. Software Systems Block Diagram

The navigation and trajectory control are based heavily on the data captured from the GPS card. Waypoints are marked in terms of latitude, longitude, and height above mean sea level (MSL). Each waypoint is also given a Stop Flag bit set either high or low. A high bit will command the vehicle to stop and hover at the waypoint once it is reached. A low bit will instruct the helicopter to continue flying through the waypoint to the next coordinate in a list. When the Stop Flag bit is set low, the velocity at which the helicopter must fly through the point is determined by the computer.

Once the desired trajectory between two waypoints is generated by the flight control program, the computer compares the actual flight path of the helicopter with the planned trajectory. The desired position and orientation at a given time is calculated and compared with the actual position and orientation. The difference between the two is the trajectory error. The control system then corrects the vehicle's attitude to return to the planned trajectory. The computer determines the accuracy with which the helicopter follows the planned course by measuring the trajectory error and its rate of change. Using a PID controller configuration, the flight control system reduces the error until the helicopter's actual flight path matches the desired trajectory.

When the helicopter flies through a waypoint, it must change the direction of travel as it continues on to the next waypoint. Instead of stopping, changing orientation, and then resuming forward flight, the ideal motion is described by an arc. The helicopter flies this curved path as it aligns its heading toward the new waypoint target. The speed at which this arc is traversed is proportional to the angle of the arc and the distance between the two waypoints.

Multithreaded Software Structure

Multithreading allows multiple program segments to run "simultaneously" on a system, frequently cycling through processes, or threads, as one thread pauses to exchange data with some outside source (memory, hard drive, serial port, etc.). Normally a program consists of a single thread, but a program can be broken up into multiple threads by using special header functions called "pthreads". The flight control software runs several threads, as shown in Figure 4.

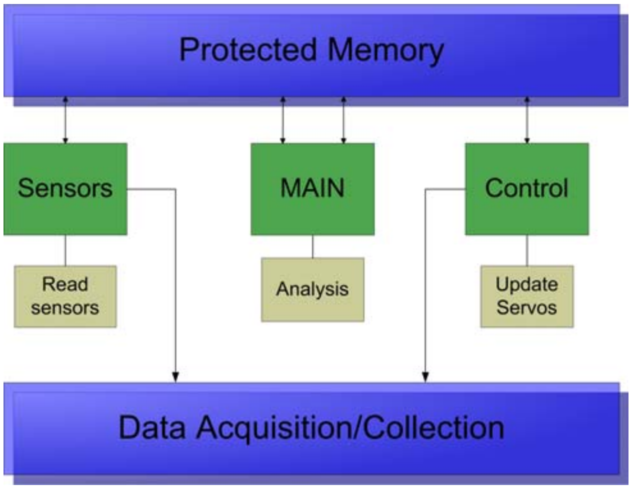

Figure 4. Multithreaded Software Processes

The three main threads are sensor data collection, analysis of that data in the main function, and servo output control. The sensor data collection thread can also be divided into several threads, one for each sensor package (GPS receiver, ultrasonic sensors, AHRS, etc.) depending on the desired configuration and performance of the system. The sensor data is collected from the various onboard sensors and sent to the data acquisition function. The data acquisition/collection routine accesses all the stored data sequentially and saves it into a CSV file for post-flight analysis.

The analysis thread accesses all the pertinent data read from the sensors and calculates the actions necessary to complete the current flight control task. The control thread reads the results of the analysis thread's calculations and translates them into servo control instructions. The instructions are then sent to the servo controller board via an RS-232 connection. The servo controller board converts the control instructions into pulse width modulated signals that reposition the servos.

The threads exchange data through protected memory. In protected memory, only one thread can access a section of memory at one time. It must "lock" the variables, make its changes, and then "unlock" the memory locations. While there are many advantages to using protected memory in a multi-threaded program, there are several extra precautions that must be taken. A specific order for locking and unlocking protected memory locations is always maintained to prevent two threads from simultaneously attempting to access the same memory block.

2.3 Emergency Flight Termination System

The large, rotating blades of the Bergen Twin helicopter present potential risks to spectators. In order to eliminate this risk, an independent emergency termination system (ETS) and backup pilot mode have been designed. The independently powered and operated ETS has been designed to ensure the safety of spectators and comply with all IARC requirements. A set of relays is used to ground the ignition, killing the engine power on command. The system is powered by an independent 6 V rechargeable battery. To make the system redundant, two radio receivers on different frequencies are used to trip the relays. Both radios are capable of transmitting as far as 7 miles, a more than sufficient range to satisfy the competition requirements [2]. The circuitry is configured in such a way that if both signals are lost the engine will lose power. When engine power is lost, the vehicle is rendered ballistic unless the radio operator is within range, in which case the pilot backup mode can be engaged with the control switching system and the vehicle can be auto-rotated to a safe landing.

3 HARDWARE SUBSYSTEMS

The Bergen helicopter carries a single onboard 1.2 GHz Pentium III notebook computer with 512 MB of memory. The onboard sensors and avionics communicate with the computer through serial and Ethernet connections. The onboard computer can be accessed externally through a network interface to modify the system setup or to retrieve data collected during flight. Data from the onboard sensors is logged during flight and stored in a comma-separated variable (CSV) file. Currently, the network connection is not wireless-enabled; however, wireless capabilities will be integrated in the future to permit telemetry between the helicopter and a ground station. A wireless network will also be necessary in the future for the dedicated ground station computer to process reconnaissance images.

All the onboard electronics, with the exception of the notebook computer, are powered by a Li-Ion battery pack capable of producing 5800 mAh at 19 V. The computer is separately powered by its internal battery. A Li-Ion battery was selected because of its extremely high power-to-weight ratio. Due to its chemical composition, the battery is not susceptible to memory loss, making it possible to recharge it at any power level without causing damage. The Li-Ion battery pack is connected to a power regulation and distribution board, which provides a fuse-protected and variable voltage output power supply. Each fuse a very fast-acting type of fuse that was originally developed for the U.S. Space Program. DC-to-DC converters and voltage regulators convert the 19 V battery output to voltage levels specified by the various electronic components. Shielded two-conductor cable, which prevents EMI from affecting power connections, is used to connect the onboard electronics to the power distribution board. A main power switch disconnects the battery from the distribution board when the electronics are not in use.

To maintain stabilized flight, the computer utilizes signals from an Attitude and Heading Reference System (AHRS) that includes 3 gyros, 3 accelerometers, and 3 magnetometers. The gyros and accelerometers describe the 6 degree-of-freedom motion of the helicopter, while the magnetometers relate the orientation of the helicopter to the Earth's magnetic poles. The AHRS is a self-contained unit that operates on an integrated XScale-based computer running Linux. The low-power CPU runs an extended Kalman filter with a 200 Hz raw update rate.

Although the autonomous flight control system could function on its own without any type of object detection sensors, an obstacle avoidance system was designed to significantly decrease the probability of the helicopter hitting any obstacles that may enter its path. Four ultrasonic sensors are attached to the exterior of the carbon fiber electronics enclosure, facing four directions: forward, left, right, and down. The ultrasonic sensors can detect objects up to a distance of nearly 12 meters with an accuracy of one centimeter. Each sensor outputs an analog voltage between 0 and 5 V that is converted to a 10-bit binary number through an analog-to-digital converter on a microcontroller board. All the sensor voltage outputs are multiplexed through the microcontroller to a single RS-232 port connected to the computer.

The GPS unit on the helicopter is manufactured by NovAtel and is capable of 1.8 m accuracy in single-point mode. Its accuracy can be increased to within 2 cm when configured in differential mode. Due to time constraints, the GPS is currently configured in single-point mode.

The servos on the helicopter are directly controlled by a microcontroller that is connected to the computer through an RS-232 serial connection. The servo controller converts simple commands from the computer into pulse-width modulated (PWM) voltages. The servo controller provides 11 bits of resolution.

4 OPERATIONS

4.1 Flight Control Mode Switching System

The helicopter and its onboard control system are capable of both manual and autonomous flight. The control switching system, illustrated in Figure 5, provides the capability to toggle between flight control modes.

The five servo motors on the helicopter are controlled with PWM signals. The manual flight control portion of the system utilizes a radio transmitter and radio receiver to control the servos through PWM outputs on the receiver. The radio transmitter is an 8-channel pulse code modulation (PCM) computerized radio that is easily configured for helicopter flight. The 9-channel radio receiver operates on a frequency of 72.410MHz, known as Channel 31 for R/C applications. The autonomous flight control portion of the system utilizes the onboard processor and a microcontroller-based servo motor controller to operate the servos through PWM outputs on the servo motor controller. A spare auxiliary channel can be activated by a switch on the radio transmitter and is used in conjunction with a PWM decoder to trip relays located on the control switching board. This board is the mechanism used to toggle the servo motor inputs between the radio receiver and the servo motor controller, thus providing both manual and autonomous flight control, by simply flipping a switch.

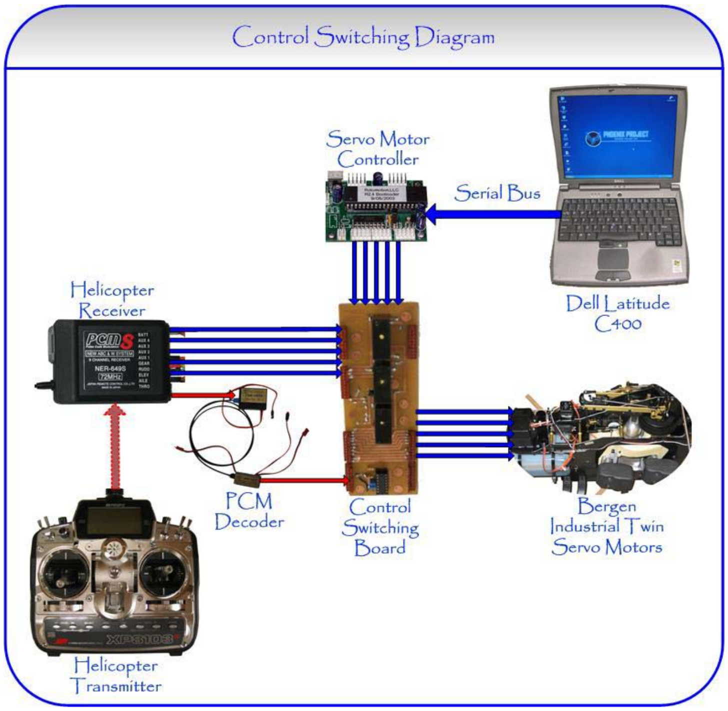

Figure 5. Control Switching Diagram

4.2 Flight Preparations

Due to the complexity of the helicopter and all the onboard systems that comprise the autonomous flight controller, careful procedures are followed before every flight. Pre-flight checklists not only include precautionary checks to ensure the mechanical systems on the helicopter are fully functional, but also verification of battery levels and an examination of the status of the electronic systems. A set of operating procedures has been written and is followed during every flight. These in-flight operating procedures include instructions for maintaining proper control of the helicopter, instructions for recovering the vehicle in case of a system failure, and detailed steps to follow in an emergency. Additionally, a post-flight inspection of the vehicle and the systems enables the team to perform timely maintenance. Safety is not only a primary concern during flight but before and after as well.

5 RISK REDUCTION

Combustion engines like the one used on the helicopter can cause disruptive levels of electromagnetic interference (EMI) and vibration. To reduce EMI, a metallic shielding fabric that is grounded to the engine case lines the interior of the carbon fiber enclosure. This also shields the electronics from potential static shock from the conductive carbon fiber. To protect the electronics from high-frequency vibration due to the engine, they are all damped with a combination of foam rubber and damping gel. The damping materials were chosen for their viscoelastic damping properties in which the damping is proportional to strain and independent of rate. These materials damp a large range of frequencies without noticeably increasing the weight of the airborne vehicle. Additional testing is being performed to verify that the actual vibration transferred to the sensitive electrical components is within tolerance.

5.1 Safety

The ETS is the primary safety feature on the current autonomous flight control system. At the touch of a button, the helicopter's engine can be disabled remotely, halting the forward movement of the vehicle. A human pilot can take over control of the helicopter as well, if it is within the manual flight radio controller's range. A set of start-up and operating procedures has also been developed to reduce the risk of injury to operators. In addition to all the precautionary safety measures, individual and system-wide testing is performed, thus ensuring that the autonomous flight control system functions perfectly and does not generate dangerous situations.

5.2 Testing

Autonomous flight imposes strict constraints. All subsystems must consistently exhibit flawless performance. The best means of reducing errors and system failures is extensive testing. The testing procedure for the Phoenix Project's autonomous flight control system begins with individual component testing to confirm that each component meets the pre-established requirements. Following the integration of the electronic systems, subsystem testing is performed to ensure all the components operate concurrently without malfunctioning. Autonomous capability testing begins with ground-based testing, followed by the use of a test stand that allows the helicopter freedom of motion while limiting that motion to a small area. The test stand ensures that the helicopter does not crash into the ground, while keeping it from flying out of range. The final step in autonomous flight testing is free flight with a human pilot prepared to take control of the helicopter in case of a system failure. Not only is the ability of the control system to maintain stable flight tested, but also the system's effectiveness at performing a variety of mission objectives and flying complex patterns.

6 CONCLUSION

The LeTourneau University Phoenix Project has begun its first year of design on an autonomous aerial vehicle for the International Aerial Robotics Competition with a multi-year strategy. The first year goal is to demonstrate autonomous flight using a helicopter as the flight system and GPS waypoints as the primary means of navigation. This paper has outlined all the systems implemented on the Phoenix Project's helicopter to make it capable of autonomous flight. Future developments to be added to the already existing system include wireless network capabilities and computer-based visual pattern recognition.

7 ACKNOWLEDGEMENTS

The Phoenix Project at LeTourneau University acknowledges the generous financial and technical contributions of our sponsors: L-3 Communications Integrated Systems, LeTourneau University Student Senate, Senix, L-3 Rivet Joint group, LeTourneau University Engineering Department, Drew Livengood, Josh Johnston, East Texas Professional Credit Union, and Downes Associates, as well as all those listed on the Phoenix Project website at www.letu.edu/phoenix/sponsors.html. The team also thanks its faculty sponsor, Dr. Greg Reynolds, for his support and assistance. Special thanks to Michael Prewitt for the generous donation of his time for flight training and helicopter-specific expertise.

8 REFERENCES

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