SMARTSONDE: A SMALL UAS PLATFORM TO SUPPORT RADAR RESEARCH

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1. INTRODUCTION

The availability of atmospheric measurements over large spatial domains provides unquestionable value to meteorological studies; however, the acquisition of such data is not always easy to achieve. One typically relies on remote sensing instruments (radars, lidars, sodars, radiometers) or in-situ probes carried by balloons or piloted aircraft. An alternative to these traditional approaches is the use of an unmanned aerial system (UAS). Research groups have recognized the benefits of adopting a UAS-based approach for making atmospheric observations and there are several on-going projects to this effect around the world.

Recently the University of Oklahoma (OU) Atmospheric Radar Research Center (ARRC) began developing a UAS platform in order to support several of its on-going research projects. It was desired to produce a platform that 1) is inexpensive and easy to deploy; 2) able to collect in-situ atmospheric measurements along either controlled or pre-configured flight paths; 3) capable of autonomous flight; and 4) supports real-time full-duplex communication (including data transfer) with a ground station. Furthermore, the design should also be one that facilitates plenty of interdisciplinary student involvement. All of these criteria have been successfully realized through a new project called SMARTSonde (Small Multi-function Autonomous Research and Teaching Sonde). As the name suggests, it is intended to incorporate SMARTSonde into a variety of research areas including measurements of the atmospheric boundary layer, the validation of radar-based estimates of atmospheric parameters, radar calibration, and so forth.

The use of a remote controlled airplane to gather meteorological data is not a new concept. Meteorologists first proposed using miniature airplanes to sample the atmosphere as far back as the 1970s (Konrad et al., 1970). Efforts to accomplish this goal faltered at that time due to a lack of compact and lightweight meteorological sensors. Today, with pressure sensors smaller than a human fingernail, the effort to create unmanned airplanes with atmospheric sensors attached has seen a resurgence. Researchers in Germany, China and the United States have begun creating miniature automated airplanes to sample the atmosphere (Spiess et al., 2007; Shuqing et al., 2004; Holland et al., 2001). The platforms developed in these countries each have a unique purpose and different design characteristics. The German design is used to verify lidar and sodar sounding profiles. The Chinese platform focuses on obtaining soundings of the atmosphere in remote areas that are difficult to measure. Other UAS platforms were designed to measure the environment surrounding mountains including upslope and downslope flow (Egger et al., 2002, 2005). However, none of these were designed expressly to sample the planetary boundary layer (PBL).

2. OVERVIEW OF THE SMARTSONDE CONCEPT

As mentioned above, the SMARTSonde concept was conceived as a means of conducting radar validation experiments by means of carrying in-situ instruments aloft along controlled trajectories and transmitting the data to a ground station in real time. The SMARTSonde design has been patterned in part after the recent work being conducted by a team of researchers in Norway, who have developed a UAS called SUMO (Small Unmanned Meteorological Observer) (Reuder et al., 2009). They use a small lightweight airframe available from Multiplex Modelsport called the Funjet. The airplane is equipped with an autopilot and GPS and carries temperature, humidity, and pressure sensors. For studies of the PBL, reliable profiles of these three quantities can already be very valuable.

For the SMARTSonde project, the NexSTAR EP Select from Hobbico was chosen for initial testing and development. The NexSTAR is sold as a trainer plane and therefore offers a robust construction coupled with the ability

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Figure 1: Picture showing the SMARTSonde airplane in flight with the National Weather Center in Norman in the background.

for stable flight patterns. It has a 68.5 inch wingspan and an overall length of 56 inches. A picture of the NexSTAR in flight is provided in Figure 1. The NexSTAR uses a 4-channel control system (motor throttle, ailerons, elevator, and rudder). The brushless electric motor version of the NexSTAR was chosen in order to avoid the potential contamination of the sensors from the fuel used to power a gas engine. Depending on weather conditions and how the plane is flown, the lithium polymer motor batteries currently being used allow for flight times of 10 - 15 minutes.

After initial testing of the airplane, we began the necessary modifications to allow flights in autopilot mode. Following discussions with the SUMO team, we decided to adopt the paparazzi autopilot system. Paparazzi is a free open-source software and hardware project hosted by the French Civil Aviation University (Ecole Nationale De L'Aviation Civile). A description of the paparazzi concept, downloadable software, and links to vendors, who provide the hardware can be found through the website `http://paparazzi.enac.fr/wiki/Main_Page`.

The paparazzi autopilot system is primarily based on inputs from a GPS receiver and infrared (IR) thermopiles, which have been oriented along three orthogonal axes. Signals from the IR sensors and GPS are fed into the autopilot microcontroller. Then, using a feedback loop algorithm, the servo motors controlling the throttle, ailerons, and elevator are adjusted such that a desired altitude and heading are achieved and maintained. A block diagram on the autopilot system and how it is integrated into SMARTSonde is shown in Figure 2.

As shown in Figure 2, the microcontroller also receives input signals from the meteorological sensors. Currently these include a pressure sensor (SCP1000 from VTI Technologies) and a combined temperature and humidity probe (SHT75 from Sensiron). Although the current manifestation of the SMARTSonde is only capable of recording basic thermodynamic data, height profiles of these values can already be used to study the development of the PBL, for example, or to validate radar retrieved parameters such as refractivity.

The SMARTSonde can fly under manual, partial autopilot, or full autopilot control mode. When in manual control (MANUAL) the plane is completely under the control of the human pilot through a conventional radio transmitter. The data communication link is active so information regarding the airplane and measurements from the sensors can be monitored. In partial autopilot mode (AUTO 1) the human pilot still has control, but the autopilot attempts to adjust the throttle, ailerons, and rudder to maintain a stable flight pattern. That is, when commands from the the human pilot are being sent to the plane, the autopilot will adjust the pitch and roll to level the plane. Here again, the data link is active. In the full autopilot mode (AUTO 2) the on-board microprocessor navigates the plane according to a pre-loaded set of instructions. The data link is active and the instruction set can be modified at any time during the flight. In AUTO 2 mode, the human pilot can only control the airplane's rudder. The conventional hand held radio controller has a three-way switch, which allows the human pilot to select the mode. Additionally, if the airplane looses radio contact or has determined that it has wandered too far from a designated reference point, then it will activate a HOME mode and try to return to an assigned location.

3. INITIAL TESTING AND EXAMPLES OF DATA COLLECTED

The SMARTSonde project is still in a testing and development phase. We have been able to successfully fly the plane in full autopilot mode (AUTO 2); however, there are still several tuning and optimizing steps to be completed before the platform can be used for routine measurements. Examples of data collected during a recent flight are shown in Figures 3 - 6. The data were collected on September 10, 2009 in the late afternoon. The plane was flown three times from roughly 16:30 - 17:30 local time (21:30 - 22:30 UT). Shortly after the last flight (around 18:00 local time) a cold front moved across the area, which brought a prolonged period of precipitation. Only data from the last of the three flights are shown. Data from the other two flights were similar to those shown.

Before discussing the sensor data, we begin by showing a sample of some of the data, which are continually

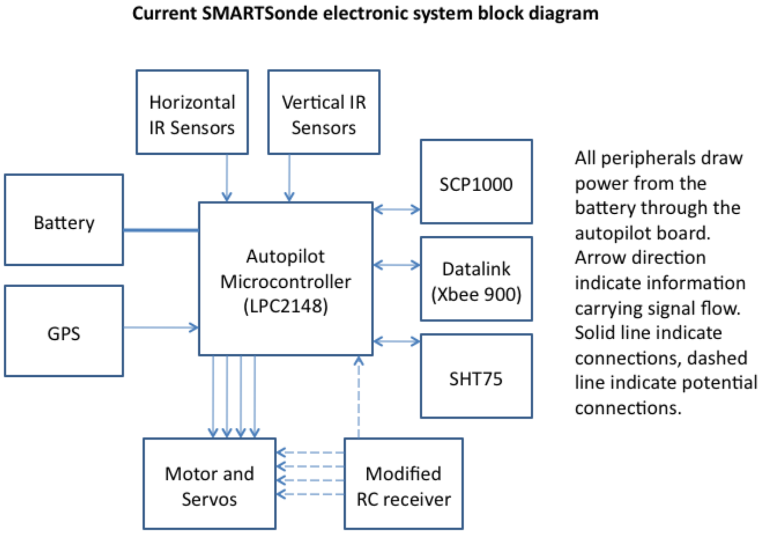

Figure 2: Block diagram of the electrical components and the control/data flow used in the current SMARTSonde system. The concept is based on the Paparazzi system.

registered by the plane's autopilot and transmitted to the ground-based computer regarding the status of the airplane. These are presented in Figure 3. The data include the position of the rudder, ailerons, and elevator, the plane's pitch and roll, the motor throttle, as well as IR data data, GPS coordinates, state of the batteries, and sensor data. All of these parameters can be viewed in real time and used to monitor the health and state of the airplane during flights. During several portions of the flight the plane was flown in AUTO 2 mode for testing. While in AUTO 2 mode, the SMARTSonde was simply instructed to hold a constant altitude while flying in a circular holding pattern around a specified way point. The height of the holding pattern, the location of the way point, and the diameter of the circle were changed several times during the flight.

Time-history traces of the sensor data are shown in Figure 4. Also shown in the figure is a representation of the flight track according to the GPS data recorded by the autopilot. For the perspective shown, it is not immediately obvious when the plane was flown in AUTO 2 mode. In fact, the flight pattern appears somewhat chaotic. Therefore, one must exercise caution when interpreting such test flight data on account of the response times of the various on-board instruments. Ideally, one should match the ascent and descent rates to the instruments' time constants. That is, accurate measurements are not expected if the plane is climbing or diving too rapidly. Maintaining a steady flight trajectory is one of the advantages of using the autopilot in the first place. Of course, having access to the height data z as a function of time, and therefore dz/dt for the plane enables us to implement filtering of the data to remove these effects.

As mentioned earlier, a frontal system was rapidly approaching during the time of the SMARTSonde measurements discussed in this paper. This is reflected in the fact that the temperature and humidity values are notably different before and after the flight. For comparison, Figure 5 shows the time histories of temperature and relative humidity measurements collected at the Norman site of the Oklahoma Mesonet (`http://www.mesonet.org/`). The Norman site is located approximately 7 km north-northwest of the CORCS airfield (the location used to test the plane). These data streams were collected 1.5 m above the surface. A sharp transition is clearly visible around 18:00 local time.

Data from the SMARTSonde flight were sorted into 20-m bins according to height and then averaged in order to produce height profiles of thermodynamic parameters, pressure, temperature, and relative humidity. These are shown in Figure 6. Also shown is a profile of the refractivity N calculated using these data. This is a useful parameter for some radar studies. The error bars denote the standard deviation of the data samples used for each average. The large values of the standard deviation of the data representing the lower heights is partly

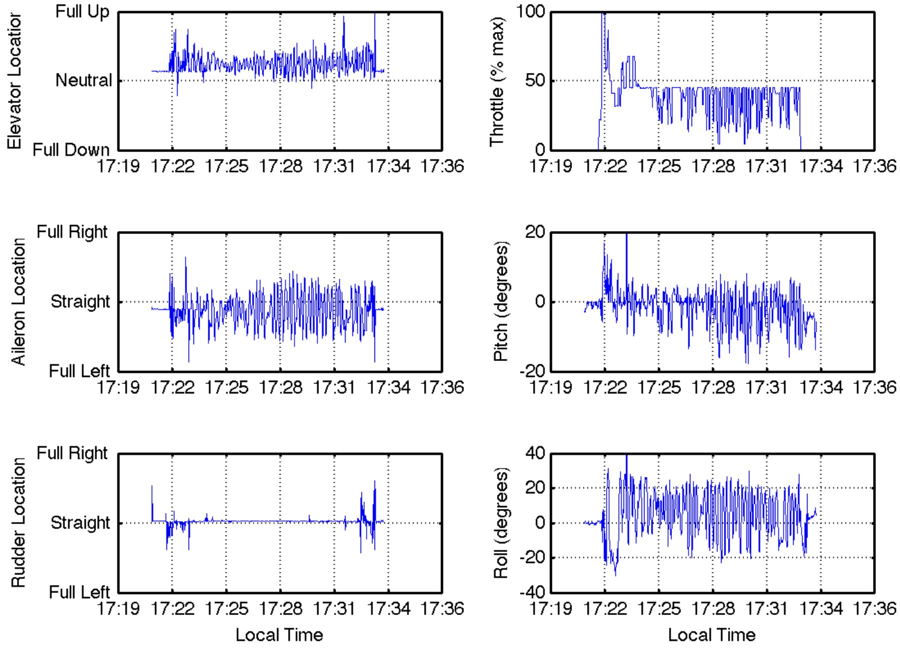

Figure 3: Sample time histories of some of the parameters, which are transmitted from the airplane to the ground station in real time and recorded.

due to the change in the meteorological conditions and partly because the plane was only briefly sampling at the lower heights and during that time it was either rapidly climbing or descending.

4. FUTURE DIRECTIONS

In order to expand the measuring capabilities of the project, a new SMARTSonde platform is currently being designed and constructed by a professor and group of students within the Aerospace and Mechanical Engineering (AME) Department at OU. Compared to the NexSTAR, the new design is smaller in size (wingspan of 48 inches), has a larger payload capacity (approximately 4.5 inches x 6.5 inches x 12 inches), and offers a more robust construction. Furthermore, it will be capable of collecting in-flight data for approximately one hour. A computer generated image of the plane is shown in Figure 7.

Meteorological instruments are mostly contained in the forward portion of the fuselage. The nose of the plane detaches to allow easy access to the sensor compartment. Having the motor on the aft portion of the fuselage insures that the backwash from the propeller does not affect the measurements. A pitot tube mounted in the wing will make it possible to record the plane relative wind speed. Other new or revised instruments planned for the SMARTSonde include improved humidity measurements using the Vaisala HMP50, ozone samples from the Aeroqual SM50, and improved temperature measurements using thermometers with faster response times. Digital cameras will also be included in order to record and archive images of the sky and ground. Both of these can impact the condition of the PBL.

An expanded electronic design is needed in order to accommodate the expanded sensor capacity. In the future design, one central microprocessor will be used for the autopilot and another microprocessor will collect and partially process data from the suite of sensors. The sensor microprocessor will be slaved to the autopilot. A block diagram is shown in Figure 8.

5. CONCLUSIONS

The SMARTSonde platform should prove valuable for studying a wide range of weather events such as dryline passages, pre-storm environments, and the development of nocturnal inversions. The data collected during those events should help us to better understand the

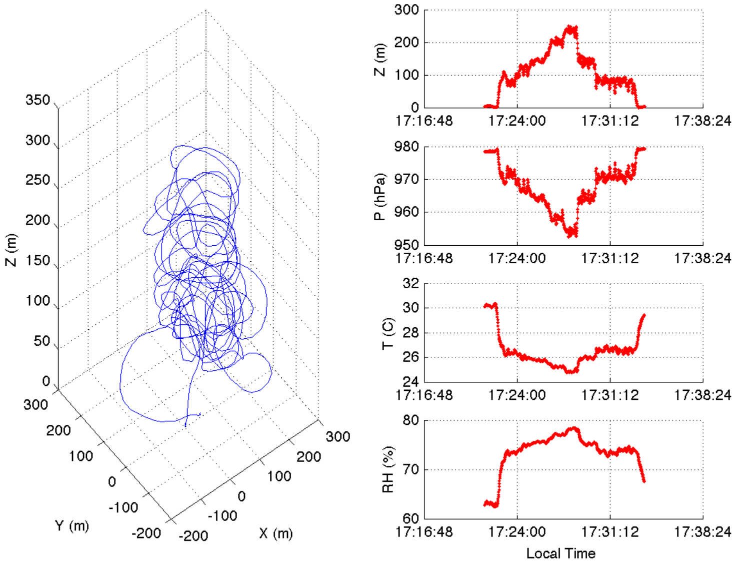

Figure 4: Record of the trajectory of the plane during the test flight discussed and time histories of the thermodynamic parameters recorded.

thermodynamics occurring within the PBL. One application currently being pursued is the validation of refractivity retrievals using weather radar. By carefully monitoring the scatter from fixed ground targets, weather radars can be used to retrieve moisture parameters in the area immediately surrounding the radar and could have an impact on operational forecasts (Heinselman et al., 2009). Although refractivity retrievals can be validated using ground-based measurements (such as from the Oklahoma Mesonet), it is also necessary to consider profiles of refractivity near the surface. The SMART-Sonde platform is ideal for such measurements.

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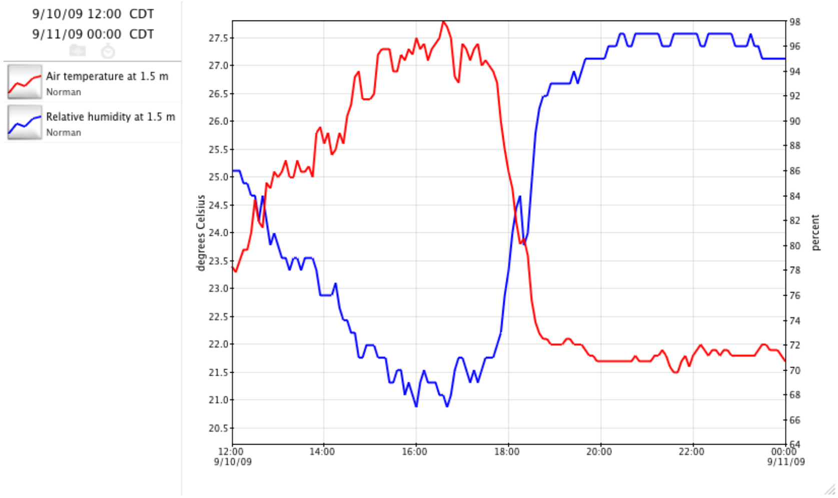

Figure 5: Time history showing temperature and relative humidity data from the Oklahoma Mesonet corresponding to the Norman site. Data are reported every 5 minutes.

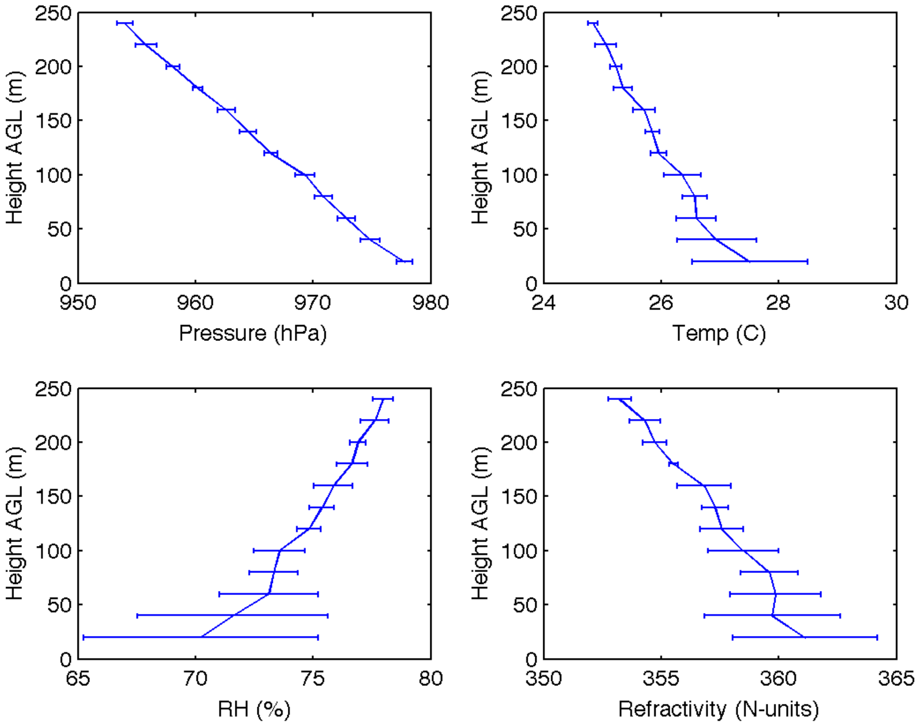

Figure 6: Height profiles of the thermodynamic parameters measured during the flight. Also shown is the retrieved profile of refractivity. The error bars denote the standard deviations of the data used to find the averages.

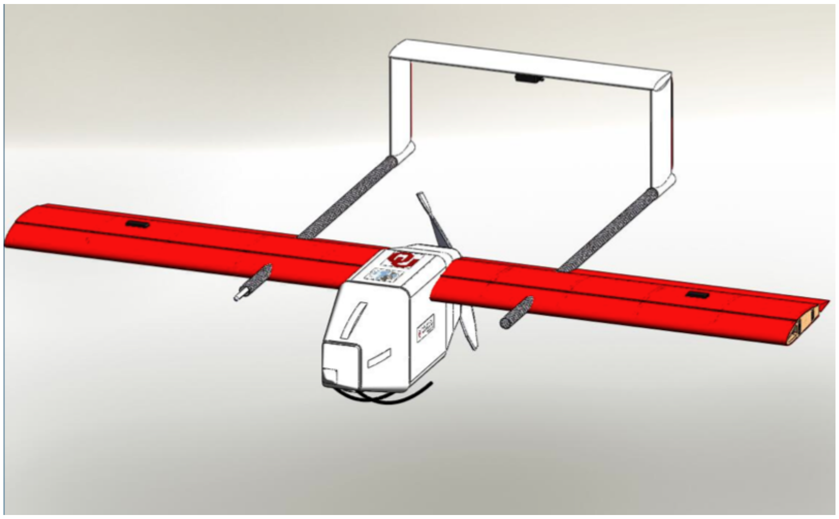

Figure 7: Computer drawing showing the design of the new airplane, which is being constructed by the OU Aerospace and Mechanical Engineering Department.

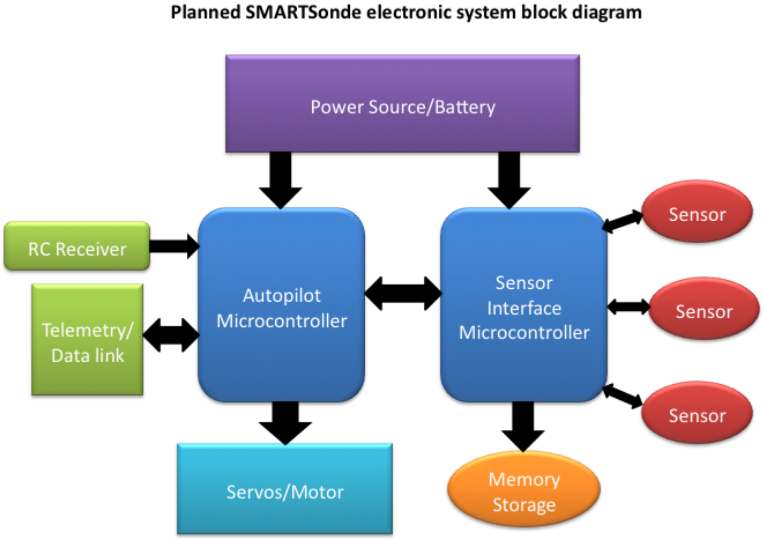

Figure 8: Block diagram of the major components and the control/data flow planned for the new airplane under construction.