Aerobot airdata measurement for planetary exploration

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Abstract

For those planets and moons that support an atmosphere (e.g. Mars, Venus, Titan and Jupiter), flying robots, or aerobots, are likely to provide a practical solution to the problem of extended planetary surface coverage for terrain mapping, and surface/sub-surface composition surveying. Not only could such devices be used for sub-orbital mapping of terrain regions, but they could be used also to transport and deploy science packages or even microrovers at different geographically separate land sites.

The technological challenges posed by planetary aerobots are significant, and the authors are investigating the design and control of helium filled balloon robots that can fly autonomously to designated landing sites. To study these problems we have constructed ALTAIR-1 which consists of a helium filled spherical balloon, and supports a robotic gondola containing a number of electronic modules. One requirement of an aerobot for planetary exploration is the ability to perform meteorological measurements. In particular, airdata, which are derived from the atmosphere surrounding the aerobot are required both for control and planetary science purposes.

This paper provides on overview of our work with ALTAIR-1 and focuses upon our research into aerobot airdata measurement for planetary exploration purposes. A number of experiments have been conducted, and some early results from this work are presented. The paper discusses the difficulties of accurate aerobot airdata measurement, and details the hardware and software tools that we have developed to investigate these problems.

1 Introduction

Whilst much attention has been given to the use of rovers for planetary exploration, most notably the NASA Jet Propulsion Laboratory (JPL) Mars Pathfinder mission and the Sojourner rover [1], the use of flying robots, or aerobots, for planetary exploration represents a highly innovative concept. Whilst rover technology is clearly competent at facilitating useful science, their application is terrain limited. They are capable of travelling relatively small distances and much of a planet's terrain is impassable to small wheeled vehicles, aerobots in comparison have no such limitations.

Consider the mission scenario depicted in figure 1. Evidence for recent ground-water seepage and surface runoff on Mars has recently been proposed [2], based upon the high-resolution images acquired by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) [3]. A mission to investigate such theories would require scientific instruments to be placed at or near a Martian 'gully', which are found typically on the interior wall of an impact crater. Such sites would be inaccessible to a rover, and an aerobot could be used to take measurements and deploy science packages. However, flying in the vicinity of these sites would require great caution due to possible turbulence effects. An aerobot would need to sample the site's airdata before descending into possible danger. Hence instrumentation is required to measure the atmosphere surrounding the aerobot. Such data can be used both for aerobot control and planetary science purposes, for example, to understand the role of aeolian processes upon the formation of these gully land-forms.

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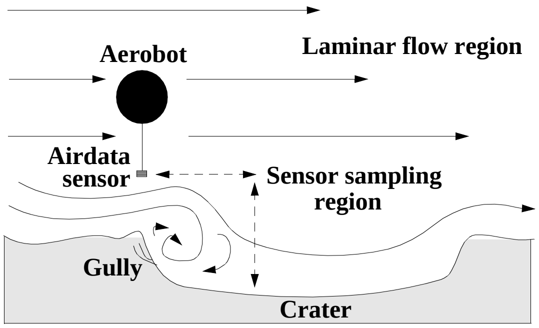

Figure 1: Mission scenario for airdata sampling.

To investigate the problems associated with flying a Mars mission, we have constructed ALTAIR-1 [4, 5]. This consists of a helium filled spherical balloon which supports a robotic gondola containing a number of electronic modules. We have designed and built airdata instrumentation that will be flown on ALTAIR-1. This paper introduces ALTAIR-1 and our research into aerobot airdata measurement for planetary exploration purposes. A number of hardware and software experiments have been conducted, and some early results from this work are presented.

2 Lighter than air (LTA) aerobot research

The simplest LTA aerobots are unmanned balloons and the first to visit other planets were the two French/Russian VEGA balloons that explored the atmosphere of Venus for two days in 1985 [6, 7]. Using only simple data acquisition sequences, these aerobots measured temperatures, pressures, wind speeds, and cloud particle properties of Venus.

Aerobot research is being conducted by the NASA JPL [8, 9, 10], who are interested in surveying planets from high altitudes due to the improved resolution of the data gathered, as compared to that obtained by orbital surveying [11]. Interest in aerobots for planetary exploration is increasing due to the ability to traverse large areas of a planet's surface rapidly, as compared to a rover vehicle.

JPL have investigated a number of sensors that are required by an aerobot such as celestial, inertial, ranging and radiometric [12]. Examples of these have been implemented on their *Planetary Aerobot Testbed* (PAT) [13] which was designed to be a flying testbed for aerobot technology. The primary purpose of PAT was to develop the telerobotic technologies necessary to fly aerobots in the atmospheres of Mars, Venus, Titan, and the outer planets. In addition, PAT was to demonstrate new science techniques such as imaging from a moving balloon.

The NASA JPL planetary aerobot activities have continued in the area of solar Montgolfiere balloons for Mars exploration [14], and ultra long duration balloons [15]. The HALE (High Altitude Long Endurance) project is a European Space Agency (ESA) airship study [16].

The NASA JPL PAT facility provided an excellent foundation for terrestrial aerobot system tests, and it is to augment this work that our ALTAIR-1 aerobot is focused.

3 ALTAIR-1 Overview

ALTAIR-1 is composed of a helium filled balloon from which hangs a robotic gondola, see figure 2. The gondola contains electronics, sensors and actuators and has a mass of approximately $1.6-1.8kg$ depending upon which experiment is being conducted. The balloon diameter required to support this mass at neutral buoyancy is approximately $1.75\,m$ and contains approximately $2.8\,m^3$ of $99\,\%$ helium at $1\,atm$. The total mass of ALTAIR-1 can reach $2.2\,kg$ depending upon experiment hardware and atmospheric conditions. The bulk of the gondola mass is a central support structure that contains servos, gears, motors, propellers and struts. The propulsion units (motors and propellers) can be vectored independently, for maximum flight control. Figure 2 shows both propulsion units in a vertical flight position. To investigate airdata

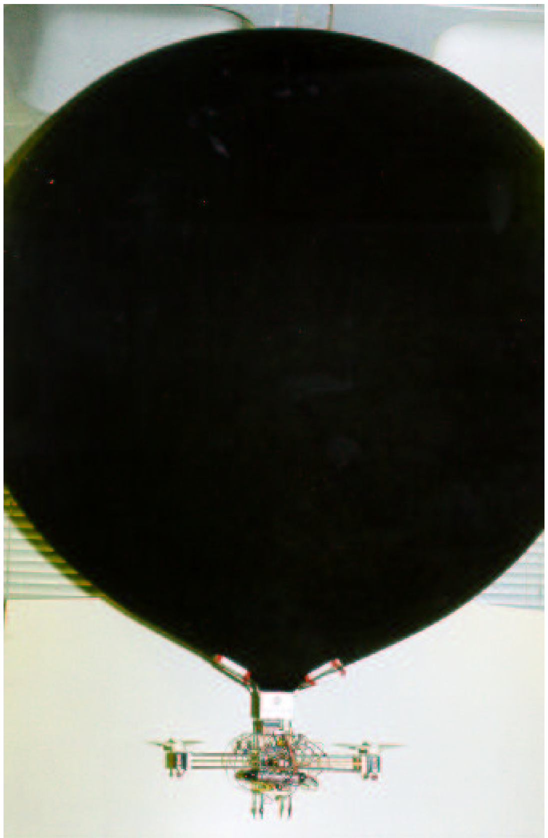

Figure 2: ALTAIR-1.

measurement, we have designed and built an electronic sonic anemometer module which is interfaced to an on-board microcontroller for experimentation purposes.

4 Sonic anemometer overview

One ALTAIR-1 electronic module that can be used for both control and science is an anemometer. This is probably the most important instrument for autonomous flight control and planetary weather science. Many different types of anemometers exist, and our research has focused upon piezoelectric oscillators which can be used as an ultrasonic anemometer. Such instruments have no moving parts, and can be designed to have low mass and power consumption. Ultrasonic anemometers measure the bi-directional time-of-flight (t_1) and (t_2) of sonic impulses travelling between two separated transmitter/receiver pairs ($Rx/Tx1$ and $Rx/Tx2$). See figure 3.

Without a wind source, the speed of a sonic pulse, C, is affected by atmospheric temperature and pressure. From Newton's second law, this velocity is given by

$$C = \sqrt{\frac{B}{\rho}}, \tag{1}$$

where B is the sonic pulse bulk modulus and ρ is the atmospheric density. Because the compressions and rarefactions of the sonic pulse occur very rapidly, the bulk modulus may be shown to be equal to γP for atmospheric pressure P. The ratio of heat capacities γ of Mars' atmosphere for example, is equal to 1.2941.

With a wind source of velocity $\vec{V}$, the effective speed of a sonic pulse, C_{eff}, relative to a stationary observer, is given by

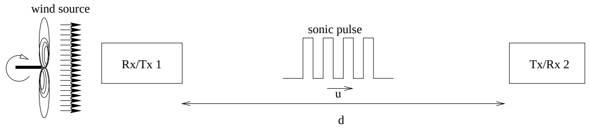

Figure 3: Schematic diagram of ultrasonic anemometer.

$$\vec{C}_{eff} = \vec{C} + \vec{V}. \tag{2}$$

From figure 3 it can be seen that the time taken for a sonic pulse to travel from $Rx/Tx1$ to the $Tx/Rx2$ transducer pair in the presence of a wind vector $\vec{V}(u, v, w)$, is given by [17]

$$t_1 = \frac{d}{\mid \vec{C}_{eff} \mid_u} = \frac{d}{C + u}. \tag{3}$$

Similarly in the opposite direction,

$$t_2 = \frac{d}{C - u}, \tag{4}$$

where d is the distance separating the transducer pairs, C the local speed of sound, and u the component of the wind source parallel to the transducer pairs' axis.

From the difference of the travel times, an expression relating the wind source component to the local speed of sound can be obtained:

$$t_2 - t_1 = \frac{2du}{C^2 - u^2} \approx \frac{2du}{C^2}. \tag{5}$$

However, where $C \gg u$, it can been seen that u is a function of the speed of sound squared, which is dependent upon atmospheric pressure, temperature and humidity.

A second method is to take the difference of the inverse of the travel times:

$$\frac{1}{t_2} - \frac{1}{t_1} = \frac{2u}{d}. \tag{6}$$

Here it is important to notice that the knowledge of C is not essential, and gives rise to an absolute measurement method that can be used for aerobot flight control. Additionally if equation 5 is used to calculate C, then from equation 1 for a given γ, planetary science data can be obtained also. The mathematical model for the ultrasound pulse flight is fully presented in [18].

With the $3D$ arrangement of six sonic transmitter/receiver pairs [19], the wind vector $\vec{V}(u, v, w)$ can be calculated, and hence a wind trajectory obtained. To date we have built a $1D$ prototype which is driven by a Motorola M68HC11F1 microcontroller[1]. This is interfaced to a PC for data acquisition and experimentation purposes. To augment our instrumentation work, we are developing our own software simulation suite that will be used to develop our ideas beyond the constraints of a terrestrial laboratory.

5 Simulation overview

We intend that our sonic anemometer be used both for planetary science and flight control purposes. To investigate such usage, we are building a virtual environment to simulate airdata measurement during autonomous aerobot flight. Our simulator uses the *FlightGear* [20] software system, see figure 4, and to create 'realistic' meteorological conditions, we are using the the *NaSt3DGP* [21] computational fluid dynamics (CFD) software package. This system can solve complex fluid flow problems, and generate typical wind trajectories for given virtual terrain boundary conditions. Generated CFD data can be checked using the *Vis5D* [22] software package, see figure 5. This is an OpenGL-based volumetric visualization

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[1] The same board used for the ALTAIR-1 flight control.

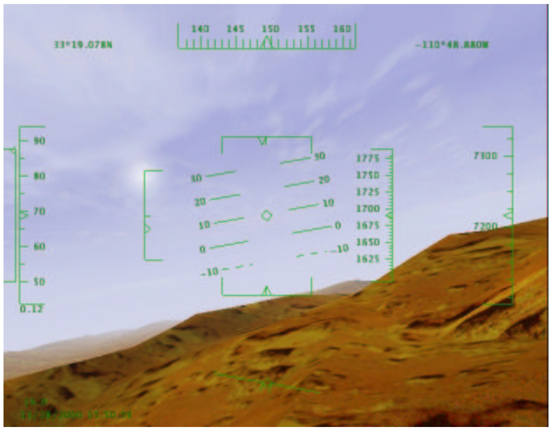

Figure 4: FlightGear screen view.

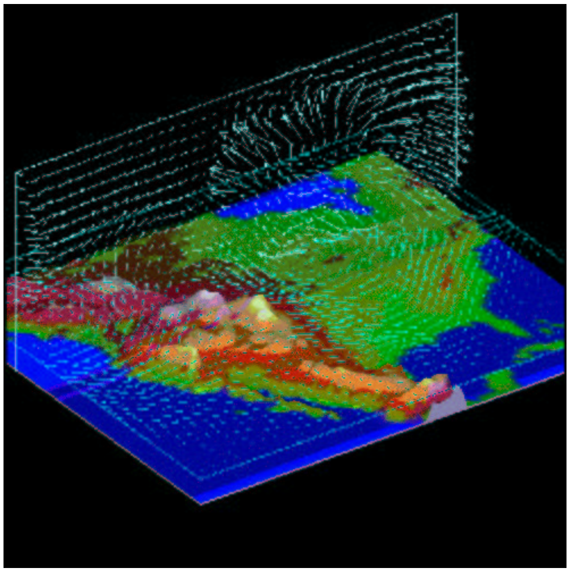

Figure 5: Vis5D meteorology data visualization.

program for scientific datasets in 3+ dimensions. The generated meteorological data can then be 'loaded' into the FlightGear simulator to create realistic wind effects upon an aerobot when flying over a given terrain. The terrain model used both by FlightGear and NaSt3DGP is obtained from the MGS Mars Orbiter Laser Altimeter (MOLA) [3] instrument, and the Mars Climate Database (MCD) [23] is used to initialise the NaSt3DGP boundary values for a given aerobot mission scenario. We believe that our use of the FlightGear, NaSt3DGP and Vis5D software packages, has created a powerful tool in our quest to investigate aerobot airdata measurement for planetary exploration.

6 Experiments and results

Using our designed and built $1D$ sonic anemometer, we have measured the wind velocity generated from a controlled laboratory wind source. Early results are encouraging due to the accuracy and linearity of the measurements obtained. Figure 6 shows a graph of bi-directional sonic pulse time-of-flight against wind source (laboratory fan) velocity. From equation 6, measured u values were obtained and compared with theoretical wind source values.

Using our software simulation environment, we have gained considerable knowledge of wind flow

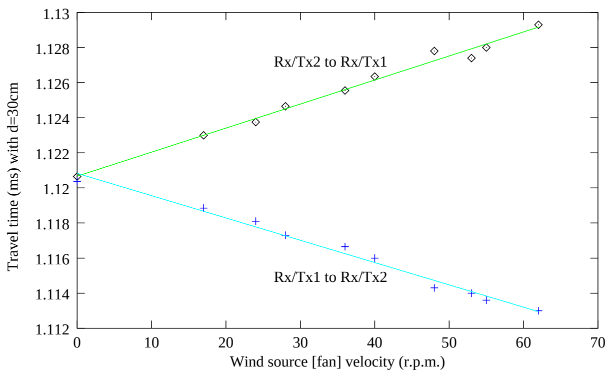

Figure 6: Graph of sonic pulse time-of-flight v. wind source velocity.

dynamics. For example, figure 7 shows a spherical balloon structure with attached gondola travelling at 3 m/s (from right to left). The balloon and gondola are shown in the centre of the figure, and are experiencing a wind of 10 m/s directed onto the balloon (from top left to bottom right) at an angle of 20° to the horizontal. Using the NaSt3DGP software package, an animation has been created by extensive iterative calculation to show the movement of the wind trail around and behind the spherical balloon and gondola structure. The figure shows a 'cut-away' through an outer isosurface (3-D contour surface) which represents the u component of the wind trajectory $\vec{V}(u, v, w)$. This has a resultant value of 6.39 m/s for this experiment, and thus represents the location of the true wind component relative to the balloon and gondola. The figure shows the distance and locations away from the balloon and gondola that a wind sensor would have to be placed to measure this true value. These large distances (approximately $1.5 \times balloon\_diameter$) from the centre of the balloon envelope are impractical, and we are investigating placing multiple wind sensors near to the balloon envelope surface. We believe that differential sensor data analysis methods can be used to obtain true wind speed measurements. Inside the isosurface, 2-D isovalues are shown around the balloon and gondola. A reflected wind component 'bow wave' can be seen in front of the balloon, with a region of lower wind component velocity behind both balloon and gondola. These results are helping us to understand both the problems associated with airdata instrument $3D$ geometry, and those problems of placing such an instrument on an aerobot. We have investigated also wind flow around a zeppelin-shaped balloon gondola for comparison purposes.

7 Conclusion and future work

Early research has been conducted in the area of aerobot airdata measurement for planetary exploration. We have designed, built and experimented with a $1D$ sonic anemometer, and encouraging results have been obtained. To augment this work, we have begun to construct a powerful software simulation tool that will allow a virtual aerobot complete with a modelled $3D$ sonic anemometer, to be flown over an extra-terrestrial terrain model, whilst being subjected to realistic meteorological perturbation. Our future work includes the build and experimentation with a $3D$ anemometer (six pairs of Rx/Tx transducers). Further research is required into the geometric arrangement of the transducers for aerobot on-board usage. NaSt3DGP investigations will be the best way to proceed with this work, prior to experiments being conducted in a wind tunnel to correct for any inaccuracies introduced by transducer mounting structures. The inclusion of 'realistic' meteorological data into the FlightGear software for ALTAIR-1 experiments requires additional work. We must further our understanding of wind flow surrounding an aerobot and interpolate, for example, the MOLA and MCD data to construct a realistic virtual planetary mission.

We believe that with ALTAIR-1, and our research into aerobot airdata measurement, we have made a small inroad into the creation of a versatile aerobot capable of both scientific data collection and autonomous flight control. The 'descendents' of which some day in the near future, may be used for real planetary exploration.

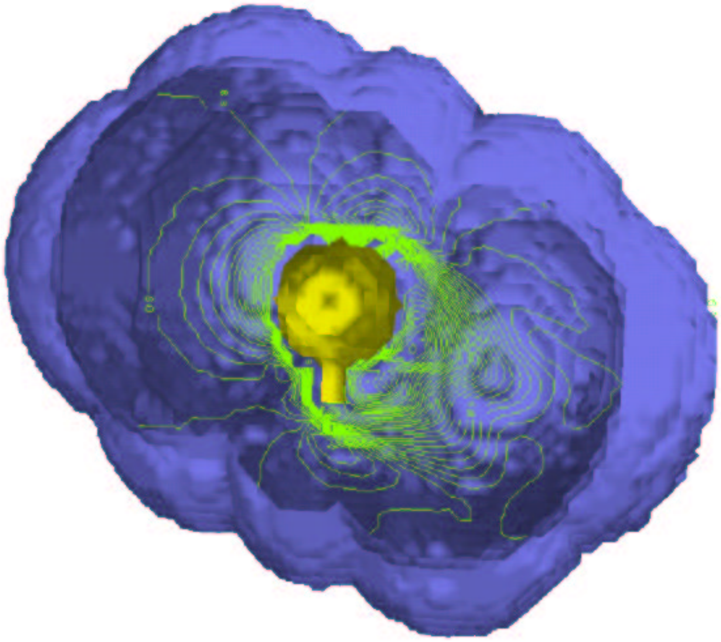

Figure 7: NaSt3DGP: 3D Navier-Stokes balloon experiment.

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