Autonomous Navigation of a Montgolfier within micro-climate on Titan

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Abstract

Ever since the Huygens probe pierced through Titan's atmosphere revealing lakes of methane and an atmospheric composition very similar to that of Earth, a second mission has been in the making. The current proposal for this new mission involves deploying a hot air balloon and taking measurements while it floats through Titan's atmosphere, which is perfect for such aircraft. However, little is known about Titan's winds. Of specific interest to this project is how to navigate a hot air balloon by altitude adjustments without prior knowledge of the winds. Terrestrial hot air balloon pilots gave insight into the techniques they use during ballooning competitions which may be applicable to a balloon on Titan. GPS data was then gathered from a variety of pilots flying towards a common goal. From this data and the geographic features of the area, a general idea of the wind currents that day, and possible causes of such currents could be determined. Comparing the data to the model of the day's wind currents can help determine the accuracy of such models.

Competitions

1. Overview

Hot air balloon pilots flying in competitions are able to navigate their balloons for nearly ten kilometers and get to within a few meters of their destination. The goal for an autonomous balloon would be for it to achieve similarly accurate flight paths with input from nothing but its onboard sensors. However, many of the techniques that hot air balloon pilots use in order to help them navigate could not be used by a hot air balloon navigating around Titan, so new solutions must be developed.

Currently proposals are for this hot air balloon to float around at an altitude of ten-thousand feet, far above any affects which the surface could induce in the wind currents. By developing methods which could be used to fly a balloon autonomously, the altitude constraint could be significantly lowered allowing for surface sampling and other scientific data to be collected.

2. Competition Techniques

Some techniques which pilots use on earth would have to be modified or lost in a flight on Titan. One of the most basic is prior experience flying in the region. General patterns in the winds can be fairly predictable at different altitudes for a specific time of day. In Bear Valley Springs for instance, early in the morning warm air flows from Bakersfield at high altitudes moving South-East across the valley. This, along with the cold air flowing North-West near the ground, allows for pilots to fly in a fairly well defined region pilots refer to as a box.

A second technique that pilots use during competition is watching other balloons and seeing how they are flying in order to determine trends in wind direction at various positions. This is one aspect of competition that will be unavailable to a hot air balloon on Titan. Even if multiple balloons were launched, over time they would spread out over far too large an area for local wind predictions to be made.

Another one of these techniques include launching a piball, which is a helium filled balloon released just before launch in order to determine the general direction of the winds at different altitudes. On Titan, it would not be feasible to continue launching helium balloons in order to detect wind direction since far too many balloons would have to be carried along for the anticipated duration of flight.

The most applicable method for Titan is altitude variation. Many pilots will ascend and descend through as many air currents as possible in order to get a general idea as to how the winds are traveling at different altitudes. In this way they are able to later adjust altitudes based on their needs.

3. Results

After the launch of a hare balloon which travels for twenty minutes before landing and placing a target for other balloonists to try and get to. A large number of balloons launch and try to throw markers as close as they can to the target. After a twenty minute flight in which the balloon traveled over four and a half miles, the pilots were able to get within feet of the target.

Figure 1 shows the yellow markers which pilots threw after their flight in relation to the large red X which was their target. The flight took place in Lancaster California the morning of September 6th 2009. At the end of the day the closest three markers were 8.6, 14.1, and 14.5 feet away from the center of the target.

Figure 1: Target for the pilots in Lancaster CA on September 6th, 2009

The morning of these flights a large group of balloons flew in a relatively straight path towards the target but a few of the balloons drifted miles off course to both sides. If a balloon on Titan were able to use the wind currents it would be able to move in one of many different directions with final destinations miles apart.

Navigational Instruments

1. GPS

Most hot air balloon pilots carry with them a small handheld GPS device capable of detecting the direction and speed at which they are traveling. Although a GPS is not needed for flight, it helps the pilots get a better idea as to the current direction of travel. When flying the hot air balloon travels with the wind so during flight any wind that is felt is likely caused by variations at the level of the gondola and not indicative of the balloons true velocity.

GPS devices will not be of any use on Titan, although through gyroscopes, and accelerometers similar directional information could be obtained. This data would be necessary for vertical control as well so that the balloon could be kept as neutrally buoyant as possible.

2. Streamers

Streamers are used by some pilots so they can watch the wind currents far below the balloon to find out when to descend into more optimal winds. They give a general idea as to the direction of the winds below although they are not very good at showing wind speed.

Figure 2: Streamers flying in the wind at Bear Valley Springs on July 4th 2009.

3. Dripper

In serious competitions some pilots use drippers which release droplets of water at regular intervals so the pilot could watch how each drop falls. This allows for the pilot to get an idea as to what the air layers below the balloon are doing. Knowing how air below the balloon acts allows for pilots to descend in order to fly in a more favorable direction.

On Titan it would be impossible to bring enough water in the balloon for the standard dripper to be useful over such a long period of time, however, if small samples of the Titan surface could be collected periodically the samples could then be used in a similar way to the water droplets on earth by dropping small quantities of dirt slowly. A camera could then be used to trace the paths of these dirt particles to reveal a little more about the winds a lower altitude.

Conditions on Titan

1. Reduced Solar Radiation

As compared to earth, the amount of solar radiation which reaches the surface of Titan is a fraction of a percentage of the amount that reaches earth. This is optimal for a hot air balloon since the lower air temperature allows for a smaller quantity of fuel to achieve the same buoyancy as on earth. This also means that slight variations in temperature could prove to have a more significant effect.

Gravity

The reduced gravitational pull from Titan means that a smaller lifting force would be needed in order to create enough lift for a balloon. This reduced requirement for buoyancy allows for smaller balloons to be utilized in order to carry the same payload, or lower internal temperature for the balloon which could extend its life.

2. Atmosphere

Another advantage of balloon flights on Titan is the increased atmospheric pressure in Titan's atmosphere. Since the atmosphere is denser on Titan then on earth the air inside of the balloon does not need to be as hot in order to create the same amount of lift. Decreasing the internal balloon temperature is very important in that a lower temperature differential across the envelope means less heat will escape increasing the balloons efficiency.

Influences on Balloon Flight

1. Geographical

One of the largest influences on the direction and speed at which wind flows is the geographical features that surround the area of flight. Large mountains can provide circulation effects which would be unlikely to arise in any other situation. In Bear Valley Springs, the surrounding mountains are able to create a box of air each morning where hot air balloon pilots are able to fly for over an hour landing in the same field they launched from.

In the early morning, warm air flows up over the valley from Bakersfield to the West, and cool air flows down off of the shadow covered sides of the hills on the North-East side of the valley. In this way, pilots are able to fly to a height of about 700ft AGL to locate winds blowing east, and descend to much lower altitudes in order to return to the landing field pictured in the foreground of Figure 3.

Figure 3: 360˚ Panoramic view of Bear Valley Springs

A second effect that mountains have on the air circulation is they lift air up on the windward side, and lower it on the leeward side. This is of great importance to balloons which travel with air currents, since nearing the leeward side of a mountain could provide for an unwanted rapid decent.

In order for a balloon sent to Titan to anticipate geographical effects at low altitudes, it would need to be equipped with radar to map out the terrain and anticipate potentially hazardous locations in order to avoid them.

2. Unequal Surface Heating

Another effect that must be taken into account is how quickly the air heats up in different regions of the valley due to solar radiation. Different areas of the ground heat up at different rates due to the surface composition, and the way in which the sun heats different areas.

Figure 4 : South facing view of a balloon decent over Bear Valley Springs.

The balloon in figure 4 is descending in order to catch the cool air patch rolling off of the small hill in the middle of the valley and change direction. A second effect taking place is over the road towards the bottom of figure 2. As a low flying balloon approaches the asphalt covered surface which has heated up significantly faster than the surrounding grass, a heat wall is formed to stop it.

The hot air rising off of the asphalt forms a barrier, which a slow moving hot air balloon may bounce off and be unable to cross. This effect can be overcome if the balloons horizontal velocity is high enough or by ascending to a location where the heat gradient has been reduced. Heat sensing equipment could be used to identify patches of warmer air although the reduced amount of solar radiation will reduce this effect.

3. Thermals

Occasionally, the heating of the earth’s surface creates columns of warm air at low altitudes called thermals. These are of great importance to hot air balloons because if they are flown through a thermal, the temperature difference between the local atmosphere and internal air will be reduced causing an abrupt decrease in buoyancy and rapid decent. If a balloon is caught in a thermal while too close to the ground, it will fall to the ground and have a rough landing with the potential of damaging the balloon or equipment.

4. False Lift

The crown (top) of the standard sport hot air balloon is curved in such a way that it acts as an aerofoil under the right conditions. When the wind across the crown of the balloon is moving faster or in a different direction than the balloon itself, a relative wind across the top creates a lower pressure than at the bottom of the balloon and a virtual lift is created. This can be dangerous for balloons as this false lift can make it appear as if the balloon is neutrally buoyant when the wind dies out causing the balloon to plummet.

False lift could be countered by placing an anemometer on top of the crown and measuring the relative wind speed. By knowing how fast wind is moving across the crown and lift coefficients for the balloons design, a reasonable estimate for the magnitude of the virtual lift allowing for precautions to be taken to prevent the balloon from falling.

5. Vertical control

Any autonomous balloon would have control over its altitude but many things need to be taken into consideration when trying to change altitudes. One problem which beginning pilots face is the delay between burning the propane, and when the hot air reaches the top of the envelope producing lift. Any control system implemented would have to take into account this delay, and must be able to predict the effects of any heat added. One example of this would be turning off the burners while descending so the balloon does not begin to rise again.

An effect which must be considered is that heat must be added even during decent so that the balloon does not lose all of its hot air and collapse. This could easily be done using the RPS by having a small amount of heat continuously supplied.

GPS track log data

GPS data has been collected and compiled from over 50 different hot air balloon flights in order to compare various flights. At the 2009 QuickChek NJ ballooning festival, three balloon flights were launched from the same area over two consecutive days. Using the program GPS Track maker, the following map of these flights was produced.

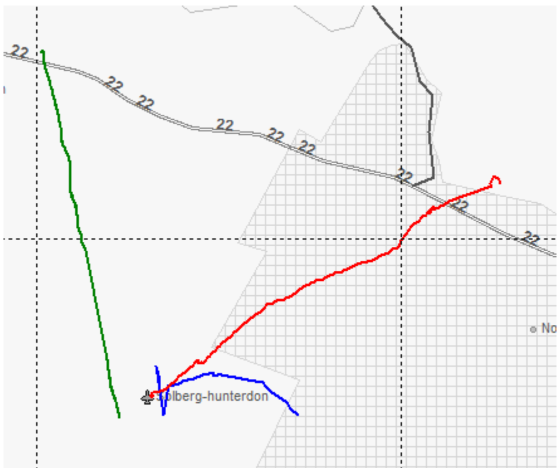

Figure 5: Track logs of 3 flights on August 24th and 25th.

The blue line in figure 5 was created from the flight on the morning of July 24th, 2009. The red line and blue lines are the paths created by the balloons 12 and 24 hours later respectively. These paths show that the time variant nature of winds in an area can change drastically over the course of a day. If a balloon on Titan could anchor itself in place, a stop for taking measurements could alter the course potentially even reversing the direction of flight. This could be used to the advantage of an autonomous balloon as it could wait for the correct winds instead of flying off course and trying to account for it later.

Another factor which must be considered is the speed at which the balloons are traveling. The green flight traveled at nearly twice the speed of the other two flights. This helped account for how straight of a flight occurred whereas slower flights such as the blue one have a much higher chance of changing directions based on time and location dependent winds. Faster wind speeds reduce the chance that slow air currents can develop in other directions which must be considered on the Titan flight which could anchor during fast winds traveling in an unwanted direction.

Instruments for Titan

1. Anemometers

Anemometers would need to be placed at various locations on the balloon in order to record slight variations in the winds. Below the gondola, an anemometer could be placed in order to determine if the balloon should descended in order to catch more favorable winds. This anemometer should be made to detect wind direction at the very least, but speed would also be helpful.

On the top of the crown a second anemometer that measured wind speed would be optimal. This way an estimate of the false lift could be determined which would allow for more precise vertical control. If we were able to know the direction in addition to speed the balloon would be able to detect good times to ascend into a slightly higher wind current.

2. Accelerometer

In addition to the anemometer, accelerometers would be necessary to determine the current velocity of the balloon. Combining this information with that gathered from the anemometers would allow the balloon to determine the absolute wind conditions along its path.

The accelerometer would also be used in order to determine the current location of the balloon and how it is traveling as well as its uses for vertical control implementations.

3. Streamers

Attaching a long streamer to the bottom of the balloon would add very little weight while still giving a much better picture of winds below the balloon. These streamers could also hold scientific equipment which may be sensitive to the heat produced in order to keep the balloon aloft.

4. Sampling anchor

Currently a dart firing mechanism is planned in order to grab surface samples during flight. One mechanism being tested uses a spring to launch is back out of the ground so that the bolt does not get stuck in the surface anchoring the balloon. However, as discussed previously an anchor which could keep the balloon in place temporarily could be of great value. With slight modifications, the spring could be latched in its loaded position after being fired at the ground letting it act as an anchor an when the latch was released spring back up fulfilling its purpose for surface sampling. By using the sampling device in this method, the balloon could get additional navigational capabilities with no extra weight. The anchor could also be used to keep the balloon in places of interest for extended periods of time in order for it to take more images of interesting features on Titan.

5. LIDAR

A technique being used in conjunction with highly competitive sailing events uses light detection and ranging devices (LIDAR) to measure wind conditions over large areas in real time. This allows the sailors to determine the optimal path into winds which will allow them to sail faster. This equipment could be included on the Titan balloon in order to measure wind fields in all directions and would greatly improve the navigational capabilities of the balloon.

It would be heavier and consume more power than the other techniques mentioned but would give a highly detailed map of wind fields that could be analyzed to determine an optimal balloon flight trajectory.

Potential for future research

The next step which must be taken in this project is to begin equipping a model hot air balloon onto which the instruments proposed can be built and tested. This would allow for experimental data for each device to be collected. Using this data practical control algorithms could be written which would be used to keep the balloon flying along on the correct path without human intervention.

One aspect which this project would be able to branch into is the testing of wind and trajectory models. By taking wind model predictions of how winds are going to act at any given time, and comparing them to the actual flight path of a balloon. A general idea as to how accurate our current wind models are can be ascertained. This could also be used in order to test trajectory algorithms such as using Lagrangian Coherent Structures to predict barriers for balloons.

Currently the WRF model is be being tested in this way using the balloon flights from multiple days to determine if the model is roughly accurate to the actual wind conditions at that time. This could help to determine how reliable current wind modeling methods are.

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