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The Use of Infrared Sensors for Absolute Attitude
Determination of Unmanned Aerial Vehicles

G.K. Egan and B. Taylor

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G.K. Egan and B. Taylor

Department of Electrical & Computer Systems Engineering
Monash University 3800
Melbourne, Australia

Abstract—this paper details how IR sensors may be used to determine the absolute attitude of Small Unmanned Aerial Vehicles under Visual Meteorological Conditions specifically the determination of an aircraft's pitch and roll angles.

Index Terms—Unmanned Aerial Vehicle, absolute attitude measurement, infrared sensors.

I. INTRODUCTION

SMALL unmanned aerial vehicles (SUAVs) have significant constraints on payload mass and energy consumption. For an SUAV to accomplish its mission it must be able to navigate and maintain control of the aircraft in doing so.

As an example, the mass of one of our SUAVs [1] empty is 5.5Kg with a typical payload of 1Kg. A significant part of the airframe mass is committed to batteries. The power required to maintain this aircraft in flight at 70Km/H is approximately 50W. The power budget for computation to navigate and control flight should be less than say 5W. The mass of the navigation and control electronics including cabling should be of the order of 200gm but much less for micro unmanned aerial vehicles (MAVs)!

As with full size aircraft most SUAVs currently rely on inertial navigation systems where measurements of the rotations and accelerations of the aircraft are used to compute updated estimates of its attitude, position and current velocities; this computation is not trivial and in our experience has the potential for catastrophic failure.

In practice it is simple to measure the attitude of the aircraft directly using infrared (IR) sensors. The justification for using the IR spectrum is set out in some detail in a prior publication describing a VMC autopilot [2].

Operation is constrained to visual meteorological conditions (VMC) that is day or night operation not inside clouds or fog. We are also exploring the use of other schemes [3] which do not rely on inertial sensors but could be used in conjunction with them as indeed IR sensors could be.

The use of IR sensors for attitude measurement of spacecraft was first published by researchers at NASA [4-8] and is directly applicable to aircraft.

The background to a patent due to Robert W. Astheimer titled 'Balance Type Horizon Sensor' [9] states, in part:

'A number of horizon sensors have been used in order to give information on the altitude (presumably attitude) of a high flying vehicle such as a space vehicle, airplane, and the like, and particularly information with respect to any deviation from level attitude with respect to two orthogonal axes representing pitch and roll.'

There is at least one commercial aircraft leveler based on IR sensors [10] which is underpinned by a Patent by Gwozdecki [11] which does not acknowledge [9] or the prior work by NASA and is therefore probably invalid. The prior work is generally directed at maintaining or restoring trimmed or level flight.

We now have several years of flight experience using IR sensor based attitude control in our VMC autopilots. This work presents how a wider range of aircraft attitudes may be determined for more aggressive aerobatic flight control. There are a few subtleties involved.

II. FLIGHT CONTROL SYSTEMS

All aircraft must be able to maintain at least level flight at some desired altitude and heading. In what follows we will assume that the reader has at least an intuitive understanding of how aircraft are controlled.

Aircraft attitude is most usually characterized by three orthogonal axes, roll being the angle that the aircraft has been rotated along its fuselage axis; pitch being the angle that the aircraft has been rotated about an axis from wingtip to wingtip and yaw the angle it has been rotated through the axes passing through the intersection of the roll and pitch axes. The axes by convention usually pass through the centre of gravity of the aircraft.

III. A COMMENT ON INERTIAL SYSTEMS

Active control of aircraft has been for some time based on inertial reference systems which also serve to provide navigation information but are now largely supplanted by GPS and other systems. It is fair to say that the rapid introduction of integrated GPS and inertial references in the automotive industry will in time lead to reduced cost for this solution.

Flight control systems (FCSs) commonly use Euler angles to represent the aircraft's attitude. If the aircraft can be contained to relatively small pitch and roll angles this is usually satisfactory. Unfortunately SUAVs and the even smaller MAVs, because of their size, can experience extremely turbulent flight conditions. If for any reason the aircraft adopts a vertical flight attitude, computational singularities can lead to computed pitch/roll angles which are 180° in error, or in simpler terms the FCS determines the aircraft to be inverted when it is not. The resulting corrective control can lead to loss of the aircraft. Of course the use of quaternions to represent aircraft attitude can mitigate these effects.

IV. IR SENSOR BASED ATTITUDE MEASUREMENT

Before proceeding it should be noted that the attitude measurements are related to the horizon and thus are Earth referenced. This does not cause any particular difficulties for the FCS in our autopilots.

A. Sensor characteristics

The IR sensors we have used are manufactured by Melexis [12] however there are a number of other similar sensors available including those from Dexter Research and Roithner LaserTechnik. They may have a range of fields of view (FOV), bandwidth and underlying sensor configurations and aperture lenses/diffusers.

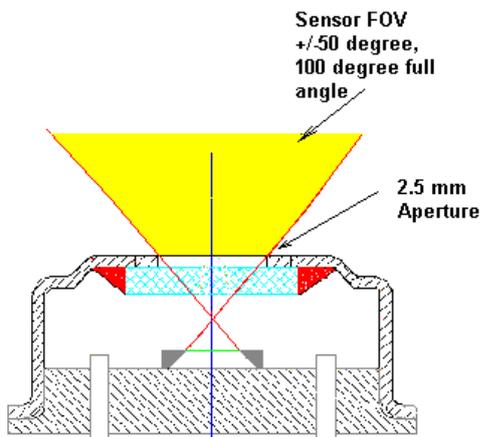


Figure 1 Melexis Sensor Field of View

The incident energy is a function of the cosine of the arrival angle at the thermopile. The aperture is circular yielding a circular illuminated area on the thermopile with the horizon forming a terminator between the sky and ground thermal images.

B. Physical arrangement

Sensors are arranged in pairs back to back facing outwards.

Usually the pitch pair is aligned with the roll axis and the roll pair aligned with the pitch axis. The spacing between sensors in a pair is immaterial. Most commonly we mount them almost back to back close to the centre of gravity of the aircraft. In the case of our previous work [2] they were mounted in the wingtips and tail.

C. Considerations for angle computation

Each pair of sensors is connected to a differential amplifier producing an analog output signal which in our case, after low-pass filtering, is fed to an analog to digital converter (ADC) for subsequent digital processing. As an aside the analog signals could be used directly with analog control surfaces in MAVs with low mass and the very demanding control response times.

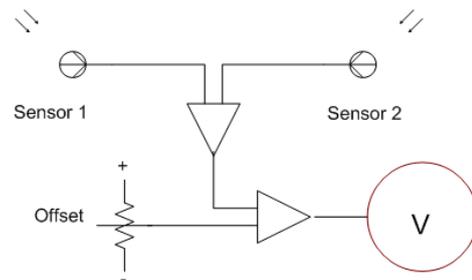


Figure 2 IR Sensor-pair

In [2] we assumed a rectangular window with uniform sensitivity across the thermopile. Under these assumptions the sensors' output signal increased/decreased linearly until the horizon fell outside the FOV of both sensors in any pair at which point the signal would be constant.

The real situation is significantly more complicated:

- the window on the sensor is usually circular illuminating a near circular area on the sensor;
- some windows have diffusers or fresnel lenses;
- the signal level at any point on the thermopile is dependent on the cosine of the arrival angle;
- for sensors without diffusers the horizon, if within the FOV, defines a chord through the illuminated circle;
- the sensor is usually composed of a grid of thermojunctions the number of which may vary;
- unfiltered thermopiles have a very wide spectral response, usually from less than $0.5\mu\text{m}$ to over $100\mu\text{m}$ and as such they are sensitive to sunlight and cryogenic temperatures. The spectral range of the sensor we use is set, at short range, by the silicon filter on the thermopile canister and at long range, by the atmospheric absorption window. These factors combined yield a nominal passband of $7.5\mu\text{m}$ to $13.5\mu\text{m}$ which by Weins' Law is approximately -58°C to $+113^\circ\text{C}$;
- the sensor window may also emit IR radiation [13] biasing the output of the sensor-pair if the heating is differential;
- the window may or may not have a flat optical passband;
- scattering and reflection occur at the input window and associated short collimator and also within the

sensor cavity and as a consequence the sensor sees changes outside its nominal FOV.

Our current conclusion from the above is that deriving an analytical model for the response of the sensors to a particular pitch/roll angle is not tractable. However diffusion at the sensor window can achieve greater averaging and thus less dependence upon the sensor geometries albeit with accompanying attenuation making matters somewhat simpler.

Figure 3 from [13] shows how sky temperature can vary with elevation under different conditions. The sensor used had a FOV of 2.9° and a bandwidth of 8 to 14 μm (89°C to -66°C).

The night sky temperature in Namibia in Africa is warmer than Durham in England where the humidity is higher as one might expect. There is no evidence of ‘flat topping’ for high elevation angles as the temperature is still within the range of their sensor. The Melexis sensor we have used may be expected to show some modest attenuation at zenith.

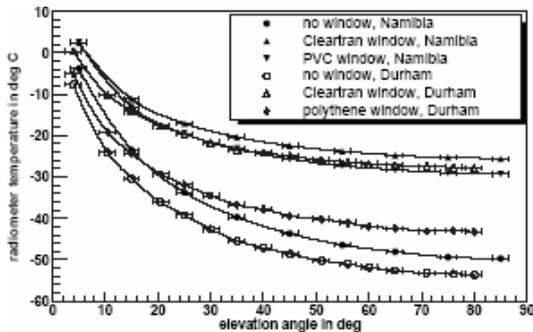


Figure 3 The relation between sky temperature and elevation angle of the radiometer with different window materials. Ambient conditions in Namibia: night time, $T = 16^\circ\text{C}$, RH 41%; Durham: afternoon, $T = 5^\circ\text{C}$, RH $(70 \pm 10)\%$ [13].

The results in Figure 3 may be extended easily for negative elevations where a sensor may see the ground.¹ If we now compute the average temperature for a sensor-pair, with no cosine arrival angle adjustment, over the 100° FOV, we obtain the results of Figure 4. Note some evidence of flattening of the curve for the Namibia case where the temperature range is less.

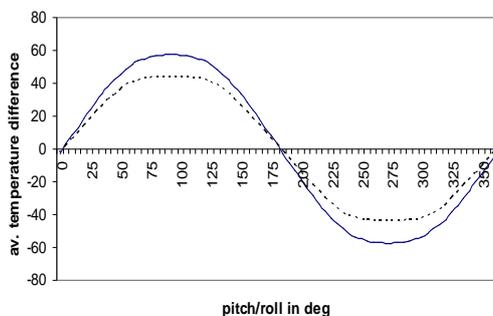


Figure 4 Expected temperature difference for a sensor-pair for Durham with a clear window and for Namibia (broken line) with a PVC window.

¹ Data points were taken manually from Figure 3 and used to compute the sensor-pair outputs of Figure 4.

For a large zenith to nadir temperature range the form of the output is in practice close to sinusoidal. If the sky becomes overcast, or there is significant cloud/fog, then the peak of the sinusoid tends to flatten. We observe this flattening in Figure 5 which shows the actual sensor-pair output for an overcast day, a trapezoidal approximation and a sinusoidal approximation scaled to peak; the maximum sensor output swing is $\sim 1.6\text{Volts}$.

Note the anomalies in the sensor-output signal most likely caused by people within the sensor FOV; these anomalies do not occur in flight.

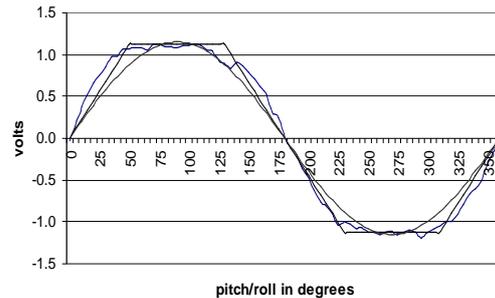


Figure 5 Differential sensor-pair output (Volts), trapezoidal and sinusoidal approximations for 360° roll (Overcast)

Formulating the likely output for a sensor-pair now appears tractable. We are currently characterizing all of our sensor-pairs for full 360° pitch/roll angles in a variety of weather conditions to augment those from [13]. We believe that it is possible to parameterise the shape of the sensor-pair output and these results will be presented in [14].

D. Current angle measurement

If scaling for an assumed sinusoid is done using the peak value then the pitch/roll values will be overestimated for low sky-ground temperature differences, which is generally a safe outcome.

If we assume a full swing sinusoid (1.6Volts) then it will give good accuracy at low angles but will underestimate high angles, a potentially dangerous situation.

Currently our autopilots assume a sinusoid scaled to the maximum sensor-pair value determined in the calibration process and as a consequence overestimate the angle for poor sky conditions.

Once the maximum output values are known we scale any subsequent output value and convert it to pitch/roll angle using an arcsin lookup table.

D. In-flight recalibration

The weather conditions as they apply to maximum sky-ground temperature differences may change in-flight.

It is possible to determine the initial maximum signals before launch by simply rolling and pitching the aircraft to 90° prior to launch and measuring the output of the roll and

pitch sensor-pairs as part of the initialization process. As noted in [2] this may be impractical for larger aircraft.

It is important to note that these output values and resulting conversion gains will almost always be different, due to partial occlusion by wings and fuselage, unless the sensors are mounted at the extremities of the aircraft e.g. wingtips. Occlusion can be mitigated by aligning the sensor-pairs at 45° to the pitch and roll axes.

Recalibration in flight can be performed by continuously tracking the maximum values. This serves to decrease the gain if clearer weather conditions occur. Unfortunately if conditions deteriorate then the angles will be underestimated. A 'leaky bucket' scheme, whereby the gain is slowly increased over time, has been shown to be partially successful although if the aircraft is flying in still air the gain may reach quite high values resulting in an initial response to turbulence which may be over aggressive. A sensible limit is placed on the maximum gain permitted in any case to moderate this. The aircraft's control surface demand in this case lasts for only a few tens of milliseconds and is barely detectable. The change in aircraft attitude caused by the turbulence resets the maximum sensor value in turn reducing the control gain.

While this arrangement has proven adequate over many hours of test flights, a far better approach is to add an additional sensor parallel to the yaw axis. The outputs from this sensor-pair may be used to determine the maximum sky-ground temperature difference which can be used to obtain suitable gains for the roll and pitch sensors. Offset scaling for the occlusion effects mentioned before are easily incorporated.

V. TERRAIN, CLOUDS AND FAILSAFE

If the aircraft is flown at low level the outputs of the sensors will be such as to result in the aircraft rolling or pitching away from any rising ground.

Low clouds, particularly those close to the aircraft and where precipitation is imminent, will similarly result in the aircraft rolling away up to the maximum programmed angle.

Both of these situations, which in our experience do not threaten the aircraft, can be detected by the use of a yaw gyro. A yaw gyro is of value in any case for controlling heading between GPS updates or for short periods during GPS outages.

There are advantages in being able to access each sensor output directly to detect these conditions and, of course, other failures including water droplets forming on sensor windows and electrical failure.

In the case of complete or partial failure of the IR sensor scheme our aircraft are designed to be intrinsically stable and will recover spontaneously from any disturbance given time and enough altitude! The techniques for designing such

aircraft are well known to the model aircraft fraternity with around a century of experience. Under these circumstances our autopilots can in most cases continue the mission or abort safely.

VI. CONCLUSIONS

The latest version of our VMC autopilot [15] with GPS unit, sensors and all cabling weighs ~105gm. Computation of pitch and roll values, expressed in around 20 lines of the C programming language, takes ~25uSec. Pitch/Roll of $\pm 45^\circ$ may be obtained reliably with two sensor pairs and beyond that for three sensor pairs. This permits proper coordinated attitude control in flight.

The power consumption is ~2W using a Microchip 18F2520 with a servo update rate of 40Hz. In line with the philosophy set out in [2], the autopilot requires minimal operator setup.

We are currently completing research on more sophisticated automatic tuning of the control loop gains. However we have found simple Ziegler-Nichols tuning will suffice, given a short period of manual flight in which the aircraft's FCS determines the various response rates.

The application of IR sensors to VTOL/3D aircraft will be described in a later paper once experimental work is complete [16].

ACKNOWLEDGMENT

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