Payload Centred Control for Unmanned Aircraft

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Abstract

Traditionally, operation of an unmanned surveillance aircraft is a two-person job. From the ground control station, an "Air Vehicle Operator" inputs heading or waypoint demands, from which the aircraft autopilot derives the low level control surface demands (typically ailerons and elevator). A "Sensor Operator" in the same ground control station independently controls the payload, which is typically a steerable video camera or forward-looking infrared (FLIR) sensor. Ideally, the Air Vehicle Operator chooses a flight path that allows the Sensor Operator a good view of the ground targets of interest. To reduce coordination problems associated with having two operators, a single operator "payload centred control" concept has been introduced. The limitations of this approach and the practical realities of implementing the concept are explored. Simulation results associated with implementing payload centred control as a layer above an existing air vehicle control methodology are presented.

Introduction

The military requirement for intelligence about the activities of opposing forces may be addressed, in part, by unmanned air vehicles operating in reconnaissance and surveillance roles. Several variants of these systems have been operated, most recently by U.S. and U.K. forces in the Persian Gulf conflict. Large area coverage can be met by high speed air vehicles with fixed reconnaissance imaging systems doing "photo-mapping"; however, small area and more immediate reconnaissance requirements can best be met by a real-time surveillance system amenable to interactive operator guidance.

Operator guidance for Unmanned Air Vehicle (UAV) systems, as currently fielded, has been implemented with very straightforward control strategies. Traditional air vehicle control loops, similar to autopilot controls used in manned aircraft, provide for air vehicle stabilization and navigation. Entirely separate control loops or systems are added for the control of the surveillance payload, which is generally a steerable imaging sensor. In this approach, two operators are employed; one to control the air vehicle and one to control the payload. The Air Vehicle Operator controls the attitude and direction of the air vehicle, while the Sensor Operator controls the attitude and field of view of the imaging sensor.

This leaves the two operators with the task of coordinating the actions of two independent systems, each with multiple degrees of freedom, often unsuccessfully. The use of two operators detracts from the performance of a surveillance system's principle task, that of imaging a given area with sufficient resolution to detect and locate all significant threat forces in the area.

The concept of payload centred control seeks to automate the management of all of the available degrees of freedom, reducing the operator's task to that of specifying control parameters that are relevant to the system's ultimate goal. For a surveillance system the logical control parameters are, ultimately, the definition of the area to be searched and the resolution criteria that must be met to give adequate assurance that threat forces can be detected. If interactive operation is required, operator control of the geographic position of the sensor footprint may be substituted for the definition of the search area. This approach combines two previously proposed control strategies, "Fly By Sensor"[1] and automated search management[2], to provide a flexible and robust control strategy.

Under the Fly By Sensor concept a single operator controls the "stare point", i.e. the geographic position associated with the centre of the sensor image, and specifies a resolution criterion adequate to his requirements for detection or identification. The air vehicle flight path, sensor pointing angles, and the sensor field of view (if controllable) are then automatically controlled to maintain the camera view position. The operator may adjust the view position using a simple two axis joystick, with commands being interpreted as position change (rate) requirements. Resolution criteria may be specified directly (e.g. in metres per pixel), or in more general terms such as low/medium/high. If the imager is a conventional daylight video camera, it may additionally be beneficial to allow the operator to specify a nominal look angle to the search area to benefit from reflection or glint phenomena. This is less critical, if not irrelevant, in the case of thermal (infrared) imagers which do not rely on illumination from the sun.

While this concept is effective in reducing operator workload, it does not fully address the surveillance requirement. While an intuitive control structure will allow the operator to control the sensor more readily, it does not ensure that he uses this control to look where he is supposed to look. Ensuring that the entire search area is adequately covered is critical to the surveillance task. To this end, the concept of payload centred control has to be extended to incorporate automated generation of a sensor footprint track, to ensure that all areas designated for surveillance will be imaged with adequate resolution and dwell time[1]. In this mode, the operator specifies the search area and the resolution requirement, and then concentrates on interpreting the imagery. Operator interaction is required only to interrupt the search pattern.

This concept is extremely attractive as a control strategy for surveillance UAVs; it provides for thorough area searches, with effective real-time operator control when required. If the control system is implemented in the air vehicle autopilot it also has the beneficial effect of minimizing communications originating from the control station, thereby reducing the probability of intercept and enemy force interference. Unfortunately, the real world, especially the flight dynamics of fixed wing air vehicles, introduces significant implementation problems. The remainder of this paper discusses the implementation requirements and the results of simulation tests run to explore potential implementation difficulties.

Implementation Concerns

Payload centred control adjusts the sensor pointing angles and field of view to compensate for changes in the air vehicle attitude and position (relative to the ground point being imaged). In turn, the vehicle position is controlled to maintain the distance from the sensor to the target within a range allowing the resolution criteria to be met. Ideally, this requires that the imager mount be able to drive the sensor axis throughout the entire range of motion of the carrying vehicle, and that the carrying vehicle be capable of maitaining a static position (or a small radius local orbit).

For a rotary winged vehicle[2], exhibiting low amplitude attitude dynamics and no minimum speed, this is straightforward; however, a fixed wing vehicle introduces large amplitude attitude dynamics, especially in the body roll axis. Body roll angles of 45 to 60 degrees can occur during unconstrained turn manoeuvres for a fixed wing UAV. This motion can readily exceed the capability of the sensor mount to compensate. The mount is often limited, in the tilt axis, to the lower hemisphere below the air vehicle body. More capable mounts, allowing for motion well into the upper hemisphere still suffer during this type of motion as the air vehicle wing (or other components of the body) may occlude the sensor field of view. Further, vehicle rates must be considered in relation to the steering rates available from the sensor. Limiting the vehicle motion to reduce the time during which the sensor is unable to image the desired point is therefore an important consideration in implementation.

1. the amount of time that an object in the field of view spends in the image. The relative motion of the object in the image must be relatively low.

2. rotary winged UAVs include the Canadair CL 227 Sentinel co-axial rotor vehicle and the Boeing Tracer tilt rotor vehicle.

Constraining the vehicle position to meet the resolution criteria can also be difficult in a fixed wing vehicle. The frequent turn manoeuvres required to place the vehicle in a local "orbit" run counter to the desire to limit the vehicle motion. Altering the sensor field of view by small increments to counter distance changes, is often not possible. Thermal imagers (FLIRs) often incorporate fixed optics allowing for two or three fixed fields of view rather than continuous zoom. In these systems, the change in the field of view is substantial, often changing the angular field of view by a factor of two or three. Further, the mechanism of switching the fixed optics is disruptive, blocking the image for a short period.

Together, these limitations of the system components present a significant challenge to the successful implementation of the payload centred control concept in a fixed wing vehicle.

Evaluation Tools

Two primary evaluation tools are being used to test the algorithms under development: a computer-based simulation, and a twin-engined general aviation aircraft fitted with a steerable video camera.

Simulation

The simulation software that is being used consists of three parts:

1. a six degree of freedom model of the aircraft dynamics
2. a simulation of the autopilot control law algorithms
3. an "electronic map" display

The aircraft model used is that of a conventional fixed wing aircraft, with a low-level autopilot. The model accepts pitch and roll angle demands as its inputs, rather than elevator and aileron demands; this is done for simplicity, and also to make the model somewhat generic. Some significant aircraft parameters, such as airspeed and roll angle limits, can be readily changed to investigate the characteristics of particular aircraft.

The higher level portion of the autopilot is simulated using algorithms which are very much the same as the actual algorithms which would be used in a UAV. A layered approach is used, such that basic aircraft and steerable sensor control laws are used as building blocks for higher level payload centred control laws.

The ongoing progress of the simulation is monitored using computer graphics in the form of a map, as shown in the figure below. Much of the code used in this "electronic map" is derived from software developed for Boeing Canada Technology Ltd. as part of a ground control station for the Vindicator aerial target system. A tail is drawn following the aircraft to show where it has been, with a result similar to what would be seen if a pen plotter were used to follow the aircraft. A rotating aircraft symbol shows the current aircraft heading. The display includes, optionally, a roll angle display, and a display of the current state of various aircraft and steerable sensor parameters. A significant feature added for the purposes of this study is

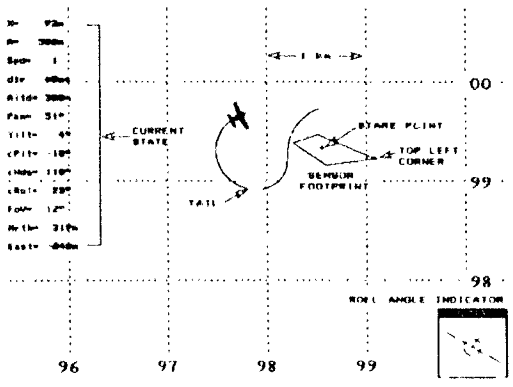

Fig. 1 Electronic Map Display

the display of the sensor "footprint", i.e. the portion of ground included in the sensor imagery.

Aircraft

Beyond simulation, trials in realistic environments are desirable to fully validate the effectiveness of the algorithms and the implementation. Especially in the case of the Fly By Sensor concept, a great deal of the evaluation and tuning will be as a result of user trials in which a payload operator is controlling the system to perform an actual reconnaissance mission. The sponsors of this work[3] operate a "surrogate UAV" system comprising a manned aircraft (Piper Seneca II) equipped with a steerable sensor mount, a ground control station, and radio data links. A computer on board the aircraft controls the steerable sensor, and performs all of the functions of a UAV autopilot (navigation, path following, etc) with the exception that movement commands for the flight surfaces are passed to the pilot. The pilot flies the aircraft, matching the requested attitude demands from the autopilot.

This approach has provided an excellent evaluation tool for the assessment of control systems, both in the air vehicle and in the ground control station. The system has been used in this configuration in the Canadian Forces field exercises RendezVous 87, Waincon 88 and RendezVous 89. Feedback from the participation in these exercises has been crucial in the definition of the detailed requirements for the payload centred control concept. Further trials of this nature will be conducted to validate the implementation of this control strategy.

Air Vehicle Control Modes

The payload centred control law algorithms that are being developed depend on lower level algorithms designed to independently control the air vehicle and the sensor platform. The air vehicle control laws required for a UAV equipped with a steerable sensor are similar to control law algorithms used in other UAVs, although some special considerations are required to address the particular requirements of the steerable sensor.

3. the Advanced Guidance Concepts Group of the Defence Research Establishment Suffield, Ralston, Alberta, Canada.

Roll Angle Demand

The lowest level control mode that would normally be used with a UAV is "Roll Angle Demand". In this mode, the ailerons are controlled in proportion to the roll angle error (roll angle demand minus measured roll angle). The control loop gain is typically constant, but could also be a function of airspeed (using "gain scheduling"). Rate and integral feedback terms are also often used in the control law. The input to this control law may be specified directly by the air vehicle operator, or it may result from a higher level control loop.

When a steerable sensor is used on the aircraft, some modifications to this basic algorithm may be required. If the aircraft has particularly quick roll response, such that the camera mount may have trouble moving fast enough to compensate, it may be desirable to limit the rate of change of roll angle demand.

Another problem which must be considered is sensor view blockage. Typically, the sensor is mounted on the bottom of the aircraft, so that with wings level, all ground targets are visible. However, at even moderate roll angles the wings could block the view to some ground targets. This problem is compounded if the mount is not capable of pointing well into the upper hemisphere of the vehicle body coordinates. Roll angle limiting can be utilized to alleviate this effect; however, the achievable turn rates will be greatly reduced unless the vehicle has lateral (rudder) control and is capable of skidding turns.

Sensor blockage, and hence the requirement for roll angle limiting, can be detected by examining the sensor tilt angle demand versus a pre-established tilt angle limit that is a function of the sensor pan angle (sensor heading relative to the air vehicle body). If this limit is approached, the roll demand should be reduced accordingly. A rudder demand can be added in proportion to the reduction in roll angle demand to maintain the turn rate.

Heading Demand

The next higher level of control is "Heading Demand" mode. In this case, a roll angle demand is generated in proportion to heading error. A rate term is not required, since heading rate is inherent in the "inner" Roll Angle Demand loop. An integral term is often used to reduce the steady state error.

If a steerable sensor that does not allow full 360 degree rotation is used, then it is desirable to avoid pan angles near the mount dead zone. The Heading Demand mode can, to a limited extent, cater to this requirement if the dead zone is aligned to the aft of the vehicle. In cases where heading demand has changed by a large amount (more than 90 degrees), it is possible to acquire the new heading either by turning to the left or to the right. One turn will be generally toward the stare point, and the other turn generally away from the stare point. To avoid the mount dead zone, the Heading Demand algorithm should choose the turn toward the stare point.

Waypoint Demand

The "Waypoint Demand" mode is used when the intention is to have the aircraft fly to a particular waypoint by the shortest route possible, without concern as to the approach direction. Implementation of this mode is particularly simple, given a Heading Demand capability. The bearing from the current aircraft position to the desired waypoint is continuously updated, and used as the input to the Heading Demand mode algorithm.

It is necessary to include in this algorithm some method of decreasing sensitivity as the aircraft approaches the waypoint, as otherwise the heading demand changes will be become too violent. One way to do this is by establishing a circular region around the waypoint, such that if the aircraft is within this area, the heading demand is no longer updated.

Track Demand

In "Track Demand" mode, the aircraft is directed to fly along a particular track, defined in terms of a track heading and a set of coordinates defining any one point along the track. Usually the coordinates are those of the track end point, although they could equally well be the coordinates of the track start point.

The algorithm calculates the heading error (track heading demand minus measured heading) and the "cross track error", i.e. the distance to the left or right of the track. These are multiplied by their corresponding proportional gain constants, and the results summed to give the roll angle demand. The heading error terms acts as "rate" term; in fact, if measured heading is not available, cross track rate may be substituted. An integral term may also be added to reduce the steady state error.

Special consideration is required if the cross track error term is very large, e.g. when the algorithm is first started. In this case, the desirable course of action is to fly at right angles to the demanded track, in order to regain the track as quickly as possible. In our implementation, this is done by calculating a roll demand using the above algorithm, and again using Heading Demand mode assuming the aircraft is approaching the track at a 90 degree angle. If the aircraft is to the left of the track, then the more negative (i.e. more "left") roll demand is chosen, if to the right the more positive roll demand is chosen.

A waypoint navigation scheme can be constructed from this Track Demand mode. In our implementation, a table of waypoint coordinates is maintained. The track demand is formed by calculating the track heading using

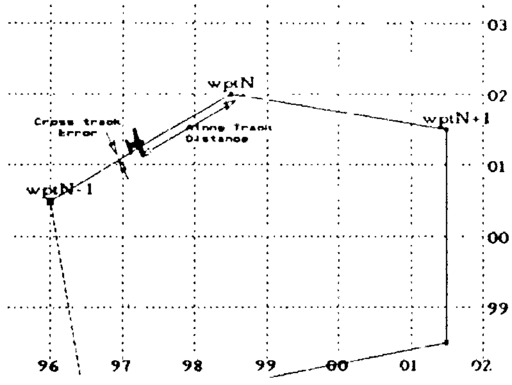

Fig. 2 Waypoint Navigation

the coordinates of waypoint N-1 and waypoint N, along with the coordinates of waypoint N. The "along track distance" (measured in the direction of the track heading, i.e. orthogonal to the cross track distance) is calculated, and used to determine when waypoint N has been reached, and hence when to update the track demand to correspond to the waypoint N / waypoint N+1 leg.

Circle Demand

Although it is possible to construct a loiter pattern using Waypoint Demand or Track Demand modes, if a circular pattern is required, it can done more smoothly using a mode designed specifically for this purpose, i.e. "Circle Demand" mode.

A circular loiter pattern is defined in terms of the coordinates of its centre, its radius, and the direction of travel (clockwise or counter-clockwise). This mode has been implemented as a variation of Track Demand mode. The algorithm first determines the point on the circle closest to the current aircraft position; the coordinates of this point, and the bearing of the tangent to the circle at this point, are then used as inputs to Track Demand mode. The cross track error term in this case corresponds to the distance between the aircraft position and the desired circular track.

In some cases the use of Circle Demand mode may be limited by the capability of the vertical gyro or attitude and heading reference system to cope with continuous turns in one direction.

Camera Control Modes

This section describes the basic control modes for a steerable sensor platform. These basic modes are used as building blocks for the higher level payload centred control modes.

Rate Demand

For an unstabilized mount, the basic manual mode of operation is pan/tilt "Rate Demand", where the mount slews at a rate proportional to the joystick deflection. This mode is generally only usable when the aircraft is in straight and level flight.

For a stabilized mount, the basic command mode is also a Rate Demand, but in this case the rates are defined in terms of a siteline stabilized to earth coordinates.

Angle Demand

In "(Euler) Angle Demand" mode, the platform is commanded to move to a position defined in terms of Euler angles (heading, pitch, and roll) in the ground coordinate system. For a non-stabilized mount, it is necessary to convert these demands from ground coordinates to aircraft coordinates, i.e. to pan/tilt angle demands. This is a relatively straightforward calculation, using the measured Euler angles of the aircraft.

With the angle demands converted from heading/pitch to pan/tilt, error terms are created by subtracting measured pan and tilt angles, and these error terms are multiplied by proportional gain constants to generate appropriate pan/tilt rate demands to the camera mount.

This is actually a type of camera stabilization, since given constant Euler angle demand inputs, the algorithm continuously adjusts the pan/tilt rate demand outputs in response to fluctuations in aircraft pitch, roll, and heading.

Angle Demand mode is of limited usefulness on its own, but is a useful building block for higher level control algorithms.

Stare Point Demand

It is often desirable to track a particular point of interest on the ground, i.e. to maintain a constant "stare point". Previous work[3] has shown this to be a useful operating mode, although problems have been experienced due to poor precision in the measured variables and due to slow sensor mount response.

Stare Point Demand mode is implemented by first calculating the coordinates of the stare point with respect to the aircraft, and then calculating the camera heading and pitch angles required to centre the camera image on these coordinates. The resultant angle demands are used as inputs to (Euler) Angle Demand mode.

This mode could be used by the Sensor Operator directly entering the coordinates of the ground target he wishes to look at. It is also useful when searching for a target, in this case the operator enters rate commands, generally using a joystick, to indicate the direction and speed he wants the stare point to move. When the joystick is released, the stare point remains fixed to allow closer examination of the sensor imagery. The result is that the Sensor Operator "steers" the sensor footprint

Stare Point Demand mode is fundamental to the payload centred control modes described below.

Payload Centred Control

Payload centred control refers to a control methodology whereby operator control inputs are expressed in parameters that are meaningful to the surveillance task, i.e. the surveillance image location and the image resolution. In other words traditional UAV control functions such as heading and altitude demands, along with sensor demands relative to the air vehicle platform, are replaced with demands formulated in terms of payload requirements. The task of determining the aircraft control required to meet these requirements is left completely to the autopilot.

Two types of payload centred control are being examined, both involving a single operator. The first of these, Fly By Sensor mode, requires operator input to "steer the footprint", but no operator input to control the aircraft. The other mode is Automated Search, where the operator does not directly control either sensor or aircraft, but instead defines his requirements at a higher level, and then focuses on image analysis/target detection.

Fly By Sensor

In "Fly By Sensor" mode, the operator steers the sensor footprint in Stare Point Demand mode, as described above. However, instead of having a second operator control the aircraft flight path, the flight path is chosen by the control law algorithm.

The approach typically taken for implementation of this mode is to establish a loiter pattern whose centre is tied to the sensor stare point. The loiter pattern then shifts with the stare point.

It may be desirable to offset the loiter pattern to one side of the stare point for a number of reasons:

1. The change in aspect angle is less, so that the operator sees a more consistent view of the target area.

2. Lighting may be more favourable from one direction, i.e. it may be desirable to avoid looking into the sun.

3. The location of anti-aircraft guns may make some locations more hazardous than others.

This type of Fly By Sensor mode has been implemented in the simulation, and is now being evaluated. Two loiter patterns are being used: circular, and alternating waypoint. The circular pattern requires generally lower roll angles, and hence is less subject to view blockage. The alternating waypoint pattern, on the other hand, offers some other advantages. By alternating left and right turns, lower demands are placed on the attitude and heading reference system (AHRS) of the aircraft. Also, if the camera mount is incapable of continuous 360 degree rotation, the alternating waypoint pattern can be arranged such that the sensor pan angle need never pass through the "dead zone" of the mount.

The circular loiter pattern is achieved with Circle Demand mode described above, using a varying centre point. The centre point is positioned at some offset distance and direction from the stare point. The offset is an operator-entered parameter, which can be varied e.g. as lighting conditions change.

The figure below shows the aircraft following a linear search pattern. The stare point was advanced at a rate of 10 m/s (moved in 100 metre increments, with a ten second pause at each step). Because the centre of the circular loiter pattern is a fixed offset from the stare point,

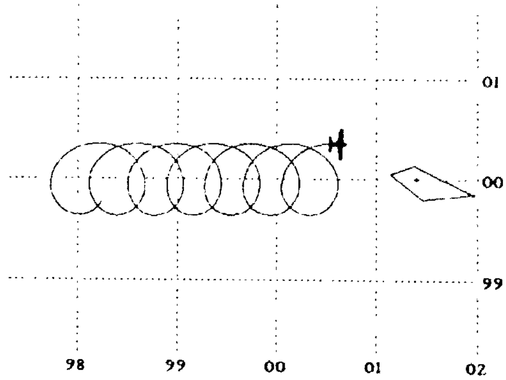

Fig. 3 Linear Search Pattern

it advances at the same rate (10 m/s). It could be said that the "effective airspeed" of the aircraft has been slowed to 10 m/s.

Fly By Sensor mode using the alternating waypoint loiter pattern is implemented using Waypoint Demand mode. The waypoints are offset from the stare point, as was the case with the circular loiter pattern. The Heading Demand algorithm is directed to favour turns toward rather than away from the stare point, which generally results in alternating left and right turns.

The figure below shows simulation results obtained using this algorithm. With the stare point stationary, the loiter pattern is in the shape of a "figure-8"; with a linear search pattern advancing in the direction opposite to the offset direction, the flight path takes on a winding, snake-like pattern.

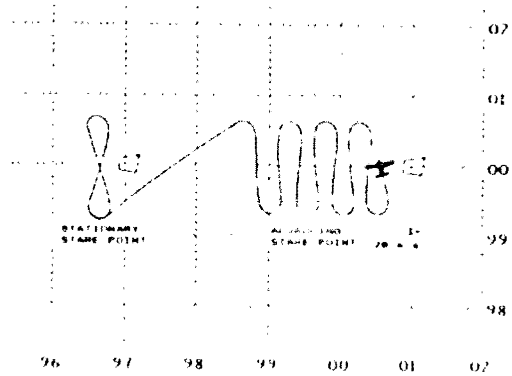

Fig. 4 Alternating Waypoint Loiter

Several different evaluation criteria are being used to measure algorithm performance. One of these is the percentage of time that the camera footprint is centred on the desired stare point, particularly for the alternating waypoint pattern, view blockage could result from sharply banked turns at the end of each leg of the pattern. It is also necessary to consider whether the resolution criteria are being met; if the aircraft travels too far away from the target, the sensor resolution may be inadequate to accomplish the specified task. Some more subjective criteria are also being used. One of these is the rate of change of view perspective, i.e. the stability of the orientation of the sensor footprint.

Automated Search

In Automated Search mode, the UAV must autonomously search a geographic area defined by a set of vertices. Image interpretation remains a responsibility of the human operator, but the autopilot must ensure that adequate resolution is achieved, that the sensor footprint remains fixed for a sufficient "dwell time" at each location, and that the entire defined region is covered.

The one approach to this problem that has been implemented to date is actually a modification of the Fly By Sensor mode described above. Operator stare point demands are replaced by a computer generated scan pattern. For example, the stare point can be automatically shifted east in 100 metre steps, with a 10 second pause at each step. After 10 steps (1 km), it can be moved, say, south 100 metres, and then back west in 100 metre steps. Meanwhile, the aircraft flies its loiter pattern, with the centre of the loiter pattern shifting with (but offset from) the stare point, no differently than if an operator were methodically stepping through the scan pattern.

If the operator sees something he wishes to examine more closely, or if he is given new orders to temporarily divert his attention to another task, then he can interrupt the sensor scan pattern to "manually" steer the footprint elsewhere, while leaving the aircraft in Fly By Sensor mode. When ready to resume, he need only press the appropriate button, and the search continues.

A limited amount of testing has been done using this mode of operation. Results have been generally good, although the algorithm often chooses an inopportune moment to switch waypoints.

Conceptually, one weakness of this approach is that the aircraft control algorithm does not make any use of knowledge that would be available to it concerning where the stare point is about to move. A more sophisticated approach to this problem would be to control the aircraft and stare point in synchronism. Algorithms to accomplish this are now being developed.

The algorithms developed will be evaluated based on the following criteria.

1. Length of time to complete the search
2. Percentage of defined area imaged for the minimum dwell time at the minimum required resolution

A key evaluation criterion should of course be the probability of detection. With the simulator, it is only possible to ensure that the resolution and dwell time requirements corresponding to a given probability of detection are met. In subsequent tests using the Seneca test aircraft with steerable video camera, further algorithm evaluation will be performed by actually measuring the probability of detection of various military-type targets under a variety of controlled conditions. This will be a somewhat less objective evaluation, since it will involve a human operator in the loop.

Conclusions

A control system concept is being developed for use in unmanned surveillance aircraft to manage the aircraft control functions automatically in response to the requirements of the imaging sensor payload. Initial simulation results have shown this payload centred approach to unmanned aircraft control to be very promising.

Work is ongoing to further develop the automatic search algorithms, and to evaluate the approach through tests using a steerable imaging sensor mounted in a manned test aircraft.

Acknowledgement

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