Self-contained Passive Autonomous Formation Flight

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Abstract

Flying in formation is a common pilot task with high workload demands, which becomes particularly difficult while operating in degraded visual environments or windy conditions. Automation of the formation flying task can reduce pilot workload and increase safety in a piloted vehicle. In addition, autonomous formation flying control technology can be applied to collision avoidance and air-to-air refueling. Sikorsky Aircraft recently demonstrated a passive, self-contained approach to automated formation flying. The first closed-loop flight of the Automated Formation Flight (AFF) system was conducted on June 4, 2010, and four data flights were completed. The flights included data runs at hover and 70 KIAS, and were flown at the Aeroflightdynamics Directorate (AFDD) of the U.S. Army AMRDEC with the JUH-60A RASCAL aircraft following an EH-60L. The sensor used to determine the relative position of the following aircraft was a monocular visual spectrum video camera mounted on the nose of the trailing aircraft. The visual analytics algorithms used to interpret the video feed and calculate the relative range, azimuth, and elevation were implemented by the United Technologies Research Center and the Georgia Institute of Technology. The control laws used to maintain the desired relative position were developed by Sikorsky Aircraft.

Nomenclature

ACVH	Attitude Command Velocity Hold
AFF	Autonomous Formation Flying
AFOSR	Air Force Office of Scientific Research
EP	Evaluation Pilot
FACS	Flight Augmentation and Cueing System
FBS	Fixed-Based Simulator
FOV	Field of View
MURI	Multidisciplinary Research Initiative
PFCS	Primary Flight Control System
ISM	Input Signal Management
HSTC	High Speed Turn Coordination
KIAS	Knots of Indicated Airspeed
RASCAL	Rotorcraft Aircrew Systems Concept Airborne Laboratory
RFCC	RASCAL Flight Control Computer
SO	System Operator
SP	Safety Pilot
VAC	Visual Analytics Computer

Introduction

Flying in formation is a common pilot task with high workload demands, which becomes particularly difficult while operating in degraded visual environments or windy conditions. Helicopters often operate in close proximity with other aircraft while flying at speeds throughout their operational envelope. Automation of the formation flying task can reduce pilot workload and increase safety in a piloted vehicle. In addition, autonomous formation flying control technology can be applied to collision avoidance and air-to-air refueling.

As an autonomous vehicle flies, it requires a reference trajectory, such as a predetermined set of waypoints or even terrain/environment interpretation during operation. Another method of guiding an autonomous vehicle is by maintaining its position relative to another object. For this application, the flight plan of the following vehicle can be entirely specified by the location of a leader or reference vehicle.

Sikorsky has developed a self-contained autonomous formation flying system that was implemented on the U.S.

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Army Aeroflightdynamics Directorate's (AFDD) JUH-60A RASCAL™ aircraft, flying in formation with an unmodified EH-60L aircraft. Emphasis was placed on requiring no leader aircraft modifications and requiring as little follower modification as possible. The sensor used by the follower aircraft to determine its position relative to the lead aircraft was a single visual spectrum camera. A video tracking algorithm interpreted the camera image and provided relative positions in real-time to an outer-loop flight control law that wrapped around the UH-60M Upgrade (UH-60MU) fly-by-wire control laws. Other than the connection to the new outer loop, there were no modifications to the UH-60MU control laws, and therefore an evaluation pilot was able to take over control at any time to fly the aircraft with all of its capabilities.

The autonomous formation flying system was developed in the Sikorsky Fixed-Base Flight Simulator (FBS) with a nonlinear GenHel UH-60MU model following a piloted lead aircraft simulation model. A visual tracking camera and visual analytics computer (VAC) were used to analyze the image of the leader helicopter and determine the follower's relative position. The relative positions were fed to the flight control computer, which provided the necessary commands to follow the leader in formation. Maneuvers, such as departure accelerations, climbs, descents, and turns were tested in the closed-loop system. The system was then implemented on the RASCAL, and flown in June of 2010 (Figure (1)).

Figure (1) AFDD EH-60L and RASCAL aircraft during autonomous formation flight testing at Moffett Federal Airfield (first flight on June 4, 2010).

The focus of this paper is to illustrate the approach of the recently flight tested self-contained passive autonomous formation flying system. The benefits and challenges associated with a passive system that is self-contained will be discussed. In addition, the benefits of extending the technology to other applications will be considered.

Integration Approach

Full authority fly-by-wire control has enabled the development of advanced flight control response types and hold modes for rotorcraft. For example, the UH-60MU fly-by-wire flight control laws incorporate velocity and position feedback loops that allow the system to hold a constant velocity or position or follow time-varying commands. This also provides a foundation for flight control laws that allow one aircraft to follow the trajectory of another, i.e. Autonomous Formation Flying (AFF). With the full authority fly-by-wire system already integrated, adding an outer loop control law (such as the AFF system) is as simple as updating the software and providing the additional sensor.

The AFF design and development process is shown in Figure (2). A visual tracking algorithm was developed based on previous visual analytics identification and tracking theory. Multiple, different, video sensors were mounted on the RASCAL aircraft and various maneuvers were flown in formation, while the pilot was in the loop (Phase I data acquisition flight test). The visual analytics algorithms were tuned based on the insight developed from the collected video data. This was an opportunity to learn the various techniques and characteristics that are unique to this application. Quite a bit was learned about the necessary design changes required to use a monocular video sensor to track the unique shape of a helicopter that is specifically designed to blend into the background environment, while flying in various lighting and maneuvering conditions.

The first step in the control law development process was to determine the optimal integration approach, given the pre-existing control laws. It was determined that the AFF system would have its own control law partition, and its commands would be summed into the co-pilot inceptor signals. This allowed the AFF partition to be tuned and integrated with no changes to the pre-existing "inner-loop." The closed-loop baseline aircraft (PFCS, FACS, ISM, aircraft dynamics, etc.) was modeled as a new open-loop system (from the AFF perspective), and the AFF system was designed with that model. Mode logic, on/off transients, and tracking performance were tuned in the Sikorsky Fixed-Base Simulator while using an estimated sensor system model.

This process also helped to define the sensor system requirements. As the sensor system (including the camera, visual analytics computer, tracking algorithm, and filtering) was tuned, it was necessary to characterize the sensor system for control law development. The control law and visual analytics (camera included) systems were then tuned together in the FBS in preparation for RASCAL integration.

Conducting hardware-in-the-loop testing allowed the team not only to learn the behavior of the system, but also to prepare for any aircraft integration issues. This approach was very helpful preparation for the closed-loop flight test phase.

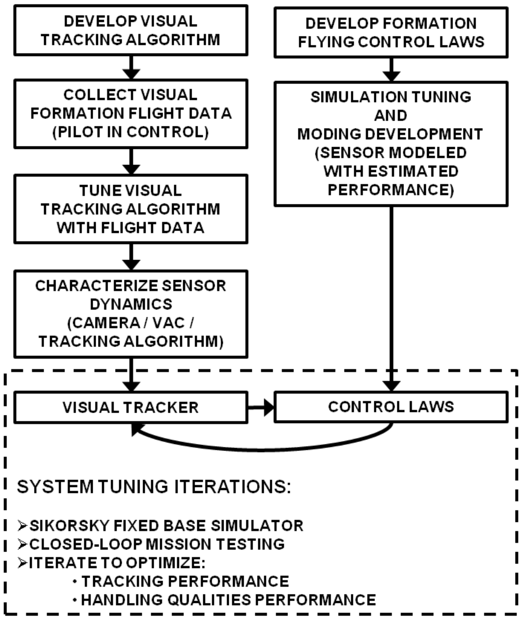


Figure (2) System design and development approach for closed-loop flight test preparation and risk management

The RASCAL JUH-60A is a UH-60A BLACK HAWK helicopter that has been extensively modified with a high-bandwidth, full-authority, fail-safe, fly-by-wire (FBW) flight control system. Developed by AFDD and NASA Ames Research Center as an airborne laboratory for helicopter flight control research, RASCAL employs a single-channel Research Flight Control Computer (RFCC) coupled to high-bandwidth, full-authority FBW actuators that drive the existing UH-60A primary servos. The single channel architecture offers flexibility and economy for rapid development and implementation of advanced flight control concepts. The system remains fail-safe because the left-seat mechanical controls are retained and are back-driven, allowing a Safety Pilot to constantly monitor the FBW system and to disengage it if necessary. Also, a high-integrity, dual-channel Servo Control Unit (SCU) constantly monitors FCC commands and responses from the FBW actuators to detect potential errant commands and malfunctions, and quickly disengage the FBW system.

RASCAL is an ideal host aircraft for the development of an Autonomous Formation Flying system. Flight control software development is also facilitated through the use of modern "Pictures-to-Code" development tools that enable tight integration between flight control law design, analysis, integration, and testing environments. The rascal research systems also provide a flexible platform for the rapid mechanical and electrical integration of advanced sensors and avionics.

Phase I Flight Test

The primary objective of the Phase I flight test was to collect video data from visible spectrum and IR spectrum cameras mounted on the nose of the RASCAL aircraft for use in sensor selection and refining video target tracking algorithms. In order to accomplish this objective, the following approach was taken:

- Mount four cameras (2 visible spectrum and 2 IR spectrum) to the nose of the RASCAL aircraft

- Boresight align the cameras parallel to the aircraft longitudinal body axis

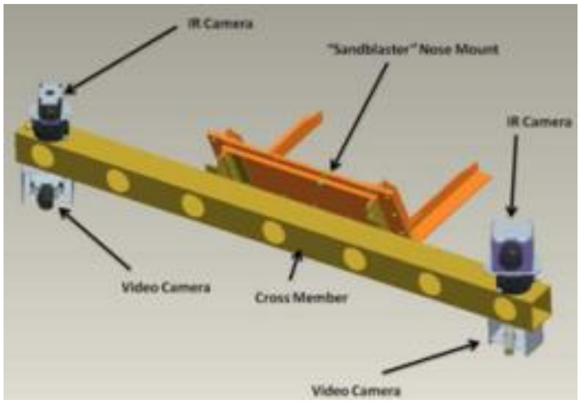
- Install a high capacity video recorder and video multiplexer in the 19" rack in the aft cabin of RASCAL to record time stamped video data

- Install video splitters and switches to enable the Evaluation Pilot (EP) and the RASCAL System Operator (SO) to view any of the images from the four cameras, or a multiplexed view of the four images, or the standard pilot display during flight

- Conduct formation flying flight tests with the RASCAL JUH-60A following the EH-60L and record time-stamped video data and aircraft state data from both aircraft.

- Calculate and display the relative distance between the two aircraft in the TM ground station to allow the Test Director to provide feedback to the RASCAL EP on station keeping performance during the tests.

The camera mount was made by modifying a previously existing nose mount from the "Sandblaster" program [11], as shown in Figure (3). All four camera mounts allowed easy adjustment of zoom, focus, and orientation. Figure (4) is a sample image from the visible spectrum cameras.



(a) Schematic diagram of camera mount

(b) Photograph of camera mount

Figure (3) RASCAL Camera mount for Phase I piloted maneuvering data acquisition flight

(a) BW Sony XC-555, 768x494

(b) Color, Axis 2420, 704x480

Figure (4) Phase I video data sample

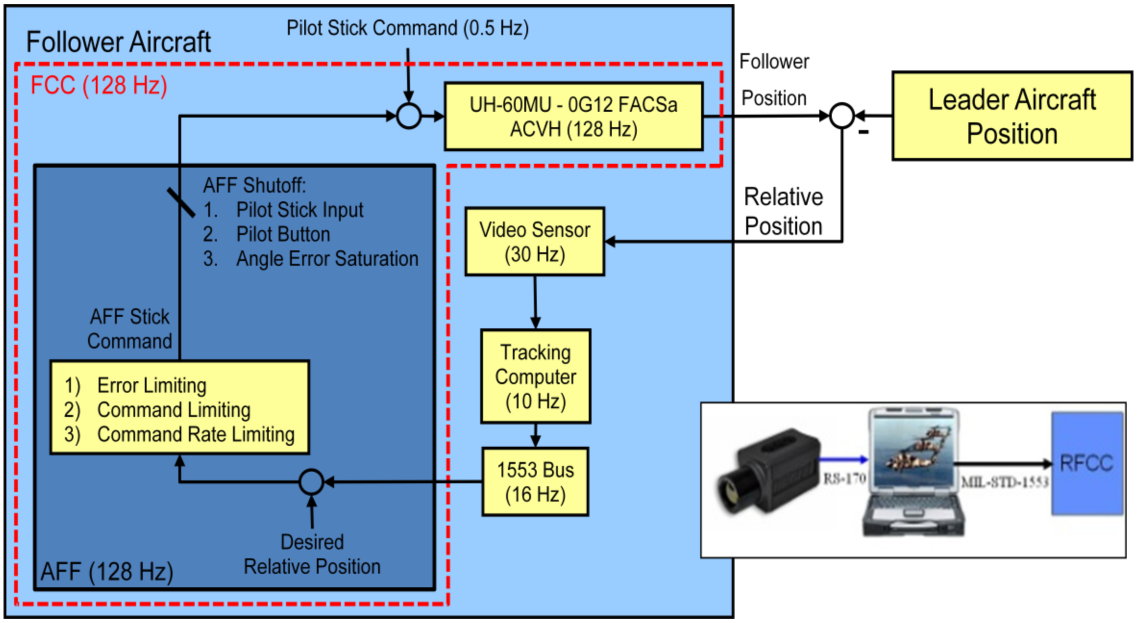


Figure (5) AFF System Level Diagram

Formation Flying Control Laws

The goal of the Autonomous Formation Flying (AFF) system is to use a passive visual sensor for relative position estimation to demonstrate the ability to autonomously follow a helicopter in formation during maneuvering flight. However, while the system is "autonomous," it is expected to be applied to manned aircraft, and is therefore subject to ride quality requirements. Because the follower aircraft modifications are intended to be simple, robust, low-cost, and as non-intrusive as possible, there were no changes to the pre-existing UH-60MU Primary Flight Control System (PFCS) and Flight Augmentation and Cueing System (FACS).

The architecture of the AFF system is shown in Figure (5). A small, light weight camera was fixed to the front of the following aircraft, and the video feed was delivered to a Visual Analytics Comptuer (VAC). A visual processing algorithm created by the Georgia Institute of Technology and the United Technologies Research Center processed the video feed in real-time to deliver the relative position of the following helicopter to the unmodified leader helicopter. The relative position information was delivered to the RASCAL Flight Control Computer (RFCC) and interpreted by the AFF control partition. The AFF system then determined the appropriate stick commands to maintain the desired relative position, and the stick commands were summed with the Evaluation Pilot (EP) stick commands.

The AFF error signals and stick commands include rate and saturation limiting in case an undetected failure were to occur and the safety pilot or evaluation pilot needed to take over. In addition, the AFF system can be manually switched off by the EP using a panel mounted engage/disengage button or by moving the cyclic out of the detent position. Furthermore, the AFF system automatically turns off when the image of the leader aircraft leaves the camera field of view (FOV). The entire RASCAL RFCS (including the AFF system) can also be disengaged by the SP, in which case the aircraft would be mechanically controlled by the safety pilot.

The AFF stick commands are used to follow a reference relative range, azimuth, and elevation. While flying in trail formation (directly aft of the leader), the range is maintained with a longitudinal cyclic stick command, and the elevation is maintaned with collective stick. Although the azimuth is maintaned with lateral cyclic stick inputs, the relationship is highly dependent on the flight condition. Lateral cyclic stick commands for low-speed flight essentially equate to lateral accelerations, while at high-speed flight, the FACS High Speed Turn Coordination (HSTC) mode in engaged. In HSTC, lateral stick is proportional to angle of bank (with FACS engaged), and angle of bank is proportional to rate of heading change. Therefore the azimuthal error can be controlled easily with heading changes. While the control inputs should be primarily single axis response, there is some coupling introduced in AFF between the relative elevation angle and the follower pitch attitude. Since the camera sensor is attached to the fuselage fixed-frame, the elevation angle seen by the camera changes with follower pitch attitude. When the follower quickly changes speed, the pitch attitude can sometimes become so large that the leader leaves the camera field of view (FOV). To compensate for this and keep the leader aircraft in the FOV over a wide range of accelerations and attitudes, an adjustable amount of elevation angle is also fed into the collective command. For example, if the follower aircraft pitches forward, it also climbs to maintain FOV.

The AFF system tracks errors on the relative range, azimuth, and elevation between the position of the two aircraft. All three references are adjustable, but the following are the default relative positions:

1) Range: 300 ft
2) Azimuth: 0 deg (trail)
3) Elevation: 0 deg (level)

The system may only be engaged when the cyclic stick is less than 5% from detent. When this criteria is met, a push-button is used to command the AFF system to engage. The system will stay engaged unless the pilot makes a stick input greater than 5%. There is also an automatic disengagement if the leader image leaves the FOV. An absolute distance error limit is imposed, but if this is exceeded, the system will not automatically disengage. The intent of the distance error limit is to restrict how hard the follower aircraft will try to follow an aggressive leader acceleration. However, for safety reasons, there is no limit on deceleration. When the AFF system disengages, there is a smooth fade to the conventional FACS reference hold functionality. Therefore, if the system is disengaged due to an elevation or azimuth error exceedance (loss of FOV), the system will smoothly come to wings level and hold speed, altitude and heading.

Monocular Vision Tracker

There are a number of possible approaches for air-to-air sensing of range, azimuth, and elevation (in either relative or absolute coordinates). These methods can be categorized as active, e.g. radar or lidar; receive only, e.g., GPS; or fully passive, e.g., using one or more cameras on fixed or gimbaled mounts.

A passive monocular visual sensor was chosen to avoid the detectability of an active sensor, and to reduce the number of sensors to integrate onto the follower aircraft. Further, a single camera requires less calibration and real-time image processing than multiple cameras. A single camera has the disadvantage of not being capable of direct range estimation. Multiple camera solutions can estimate range by triangulation, e.g., by stereo vision, but the range accuracy depends on the baseline (aperture) and this is quite limited for the geometries of the rotorcraft leader-follower problem.

The visual sensor requires associated analytics to track one or more aircraft in the Field of View (FOV). The analytics must produce outputs with an accuracy, an update rate, and with bounded latency sufficient for stable, robust closed-loop control. As with any sensor, the analytics must be capable of task-specific interference and clutter rejection. In the case of formation flight, the trailing rotorcraft is typically in echelon formation slightly above and offset from the leader’s direction of motion. Echelon formation naturally gives a look-down perspective and allows significant ground and terrain clutter in the field of view.

Elevation and azimuth are relatively straightforward to compute based on the position of the leader aircraft in the video field of view and the attitude of the follower aircraft. Range is calculated based on knowledge of the geometry to the lead aircraft and the tracker’s determination of the visible size based on an active contour outline of the leader aircraft image. No attempt is made to predict the leader movement based on changes in leader attitude, but some compensation is applied to the measurements based on follower aircraft attitude.

We chose to adapt and develop an active contour tracker approach used previously on an AFOSR MURI by Prof. Allen Tannenbaum and Prof. Eric Johnson of the Georgia Institute of Technology [6, 7, 8, 9, 10]. Prof. Tannenbaum and his students have subsequently improved this method and have applied it to other problems [3, 4, 5]. An example of a detailed active contour around a BLACK HAWK during a pedal turn at 300’ is shown in Figure (6a). Figure 6(a) is for illustrative purposes only; an active contour with 500 points captures significant spatial detail, but is too slow to compute in real-time.

We use an active appearance model to detect and track the leader. Here, the appearance model is the difference in probability density functions (PDFs) between the leader and the visual background immediately surrounding the leader. The size of the area around the leader is a tunable parameter, but performance was relatively insensitive to the chosen value. In normal operation, an active contour of the lead rotorcraft is determined at each video frame, see Figure (6b). The contour is evolved to maximize the statistical Bhattacharyya difference between the inside of the contour and the immediately surrounding area, see Figure (6c). The contour then visually segments the leader from the background. The contour centroid gives relative azimuth and elevation; the contour size gives range. A separate process is used if the system loses track. In that case, a Bayesian detection system attempts to re-acquire the lead rotorcraft. This latter process was not used during flight test.

In determining the leader and background PDFs, spatial kernels are applied so that the center of the leader has the most influence on the leader's histogram computation, while the outside boundary has largest effect on the background histogram. Additionally, random noise is added radially to reduce the chance that the active contour would “leak” into the surrounding clutter.

The key assumptions behind this work are that the appearance of the lead rotorcraft will be distinct from the background and will only vary slowly with respect to the video frame rate. The first assumption leads directly to the limit of performance of this method – when the leader's appearance is statistically similar to the visual background, tracking may be lost (see Figure (6b)). A more subtle instance of this limitation occurs when part of the leader's appearance changes, e.g., due to illumination or size in the field of view. In this case, the tracker may lock onto only part of the leader's image. These limitations will be discussed in more detail subsequently.

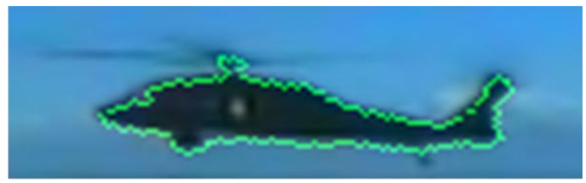
One significant difference between this work and the previous fixed-wing AFOSR MURI work is that the leader is relatively much closer to the follower. In this case, the leader may accelerate and move across the field of view quite rapidly and the leader's dynamics must be considered for good tracker performance. Maintaining lock as a target accelerates rapidly and moves fast is a classical reference-input tracking problem and, to make matters worse, in our case the target motion model is unknown. To solve this, an error-integral reference estimator was developed. The estimator is used to initialize the segmentation.

The development of any video analytics depends strongly on the representativeness of the data used for development and validation. Multiple data acquisition activities were performed, first in Sikorsky's Fixed-Base Simulator (FBS) and later at the U.S. Army Aeroflightdynamics Directorate (AFDD) on their JUH-60A RASCAL aircraft at NASA Ames, Moffett Field, CA. The data acquisition flights were designed to capture a complete set of aircraft relative positions, visual backgrounds, and ambient conditions (illumination, weather) with various cameras (resolution, color, and spectrum). Example imagery is shown in Figure (4). The algorithms were developed and tested in the FBS using only the visible spectrum cameras.

The algorithms were implemented on a rack-mounted Video Analytics Computer (VAC) PC running Windows XP. The VAC was adequate for the required 10Hz update rate, although a non-deterministic OS is not the preferred choice for real-time computation. The VAC was connected to the flight control computer (FCC) over a standard 1553B bus. The VAC and FCC run asynchronously, also not the preferred choice for deterministic timing. The video was captured with a COTS ADLINK frame grabber. The frame grabber, VAC computation, and 1553 communication were pipelined resulting in up to 3 frames latency (0.3s at 10Hz).

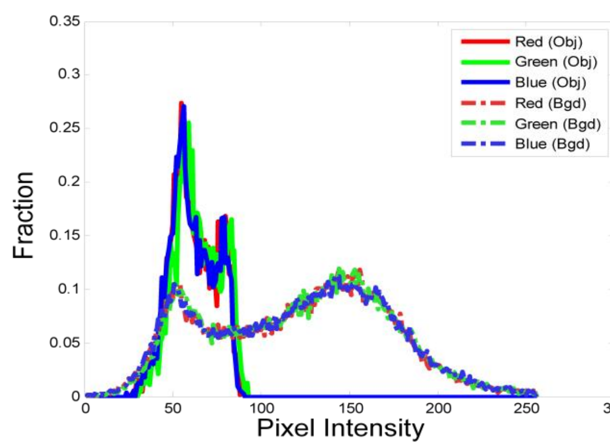
There were two generic instances where the tracker did not perform adequately: when the leader effectively disappeared into visual clutter and when the leader was sufficiently close to the follower that the visual statistics across the leader were, themselves, more statistically distinct than the differences between the leader and the background. In the first case, the tracker could lock-up on the background and lose track. This is illustrated in an FBS simulation in Figure (7). A notable instance of this problem occurred in flight when the leader was flying low in front of trees where the scene was strongly backlit. In the second case, the tracker could lock-up on only part of the leader. This did happen at close range when the leader filled a significant portion of the field of view. The problem was exacerbated under particular lighting conditions where the leader was strongly illuminated from a relatively low angle. The incorect lock-up resulted in slightly biased estimates for azimuth and elevation, and large errors for estimated range.

Improvement in tracking a leader through visual clutter may be achieved by incorporation of additional prior information. A particularly promising approach would be to use the leader's known shape [1,2].



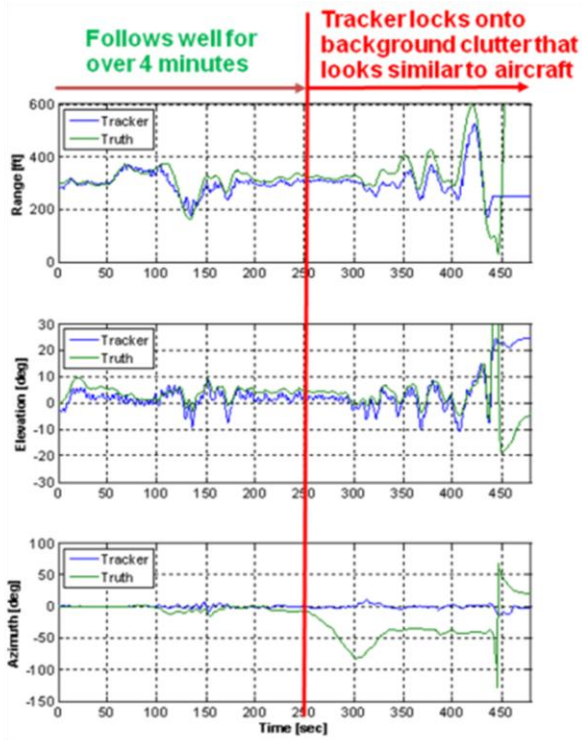
(a) Active contour with 500 points

(b) Cropped actual image with active contour

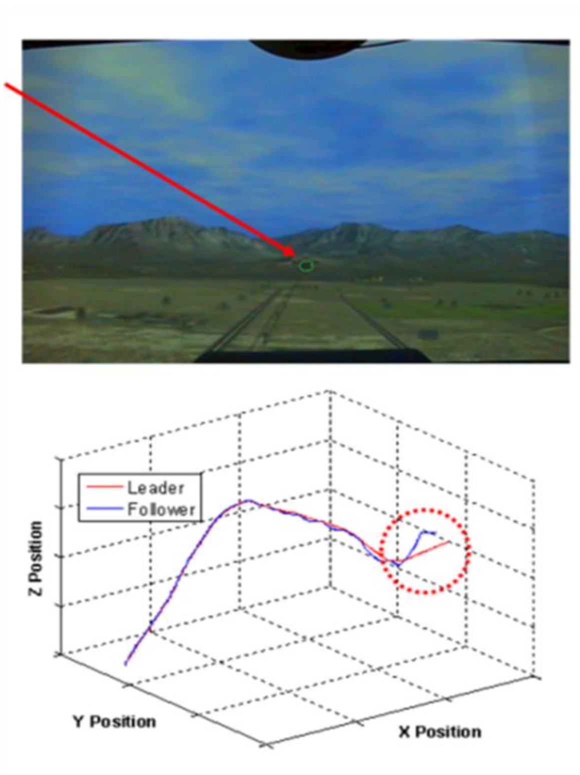


(c) Color histograms inside and outside contour

Figure (6) Kernel weighted histogram of active contour pixel intensity



(a) Azimuth, elevation, and range



(b) Image of leader in FBS and track

Figure (7) Simulator formation flight and visual tracking performance with a highly cluttered background

Closed-loop Results

Simulation Results

Closed-loop formation flight performance of the current AFF system is highly dependent on how aggressively the leader aircraft maneuvers and how much the leader aircraft blends into the background. Visual tracker performance tends to improve if the leader aircraft is not moving too quickly across the FOV while there is a cluttered background because the tracker parameters can be allowed more time to adjust. In the case of non-cluttered background (up and away flight with a clear sky background), the system is capable of following through relatively aggressive maneuvers. Figure (8) depicts a simulated maneuver in which the AFF system is initialized while at hover and close to the ground in a valley surrounded by mountains. For this case, it is necessary to accelerate and perform a helical climb trajectory to avoid the terrain and leave the flight field. It is shown that this task can easily be performed with favorable (high contrast) visual background clutter. However, this is the optimal case, and the intent of the system is to be able to follow during difficult conditions and degrated visual environments (DVE).

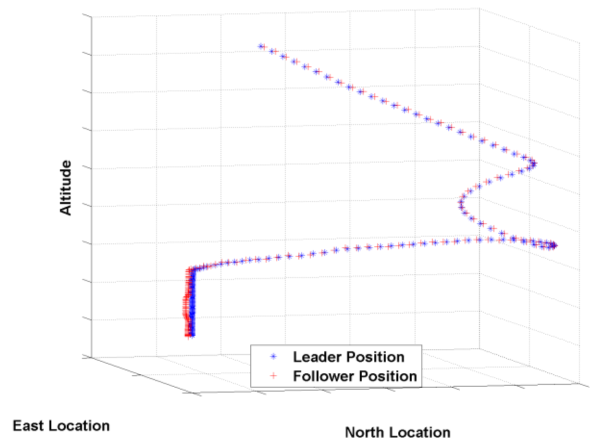


Figure (8) Simulation of automated BLACK HAWK following a piloted leader aircraft during acceleration and a helical climb maneuver

It should be noted that the challenges seen with the closed-loop system in the FBS were highly similar to the issues seen in real flight. This was a major help for pre-flight system development and risk reduction. Figure (7) shows a similar simulated maneuver with a highly cluttered background. The acceleration during the depart from hover is slower, but the follower aircraft is able to track for approximately 4 minutes including a climbing turn maneuver, but as the leader aircraft moves through some highly similarly colored background, the tracker locks onto the background.

Flight Test Results

Corrections can be made to help the visual tracker stay with the leader image through extremely high amounts of clutter. However these corrections tend to create inaccuracies in the range estimation (the azimuth and elevation remain accurate). Figure (9) shows such a case during flight test in which the visual tracker is able to stay with the leader aircraft through a cluttered background, but there is an inaccurate "jump" in the estimated range. This would suggest that a possible future system could benefit from a fusion of multiple sensors. For such a case, it may be possible to use the visual tracker to determine the azimuth and elevation, while perhaps using a sensor combination to determine the range with higher dependability.

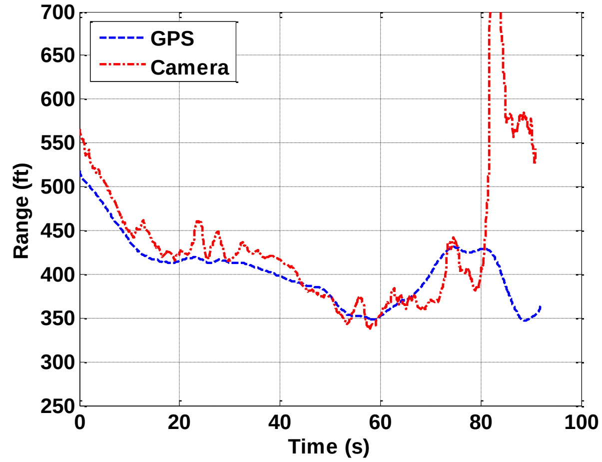


Figure (9) Visual tracker performance

Although background clutter can sometimes cause challenges, the system performed fairly well for the low clutter case. Figure (10) shows a case in which both aircraft were flying "up-and-away" at approximately 70 KIAS in trail formation with a separation distance of approximately 600 ft when the AFF system was initialized. The desired relative position was 350 ft. For this case, the EP reported an acceptable ride quality when moving to the desired relative position, despite winds of about 15 kts.

Figure (11) shows the follower tracking performance through a turning maneuver. The aircraft are flying in trail formation at approximately 70 KIAS when the leader aircraft makes a heading change of approximately 100 degrees. It can be seen in Figure (11) that the follower aircraft reaches a maximum angle of bank of about 15 degrees during this maneuver.

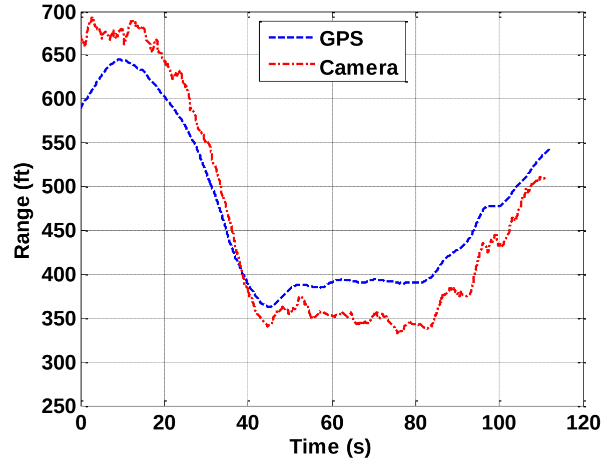


Figure (10) Visual tracker performance

Conclusions

The Sikorsky Autonomous Formation Flying system was demonstrated on the JUH-60A RASCAL aircraft in June of 2010. The demonstration showed the feasibility of using a monocular video sensor with a full authority fly-by-wire control system to maintain formation with another aircraft. The AFF system was tested with a variety of clutter versus no-clutter backgrounds, windy versus calm air, and multiple weather lighting conditions to test the limits of the current AFF system and to learn what improvements and next steps can be employed. Overall, the visual tracking system demonstrated acceptable performance in azimuth and elevation, but the variation in the range value was excessive and prevented long duration operation of the system. Additional testing is planned to improve the visual tracker performance, to explore the use of alternative sensors and the potential for active and passive sensor blending, and to better judge the limits of the application for future systems.

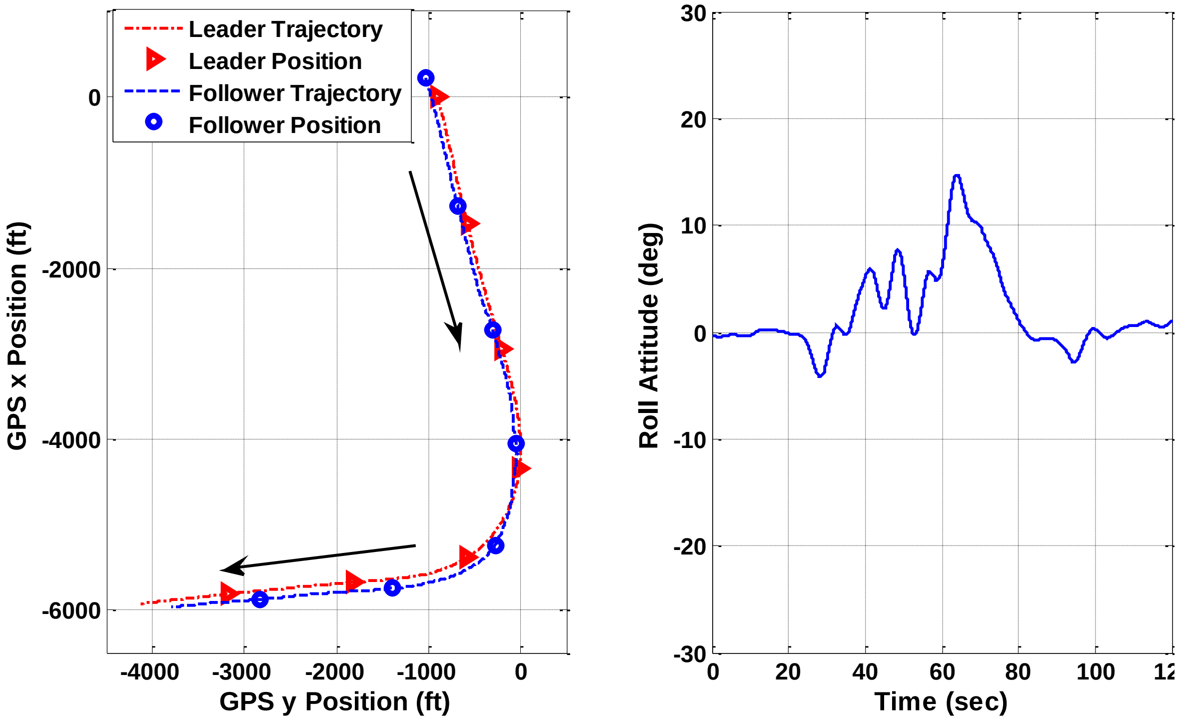


Figure (11) Following in trail formation during a level turn maneuver (70 KIAS)

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