Contributed paper

Pilot safety enhancement for on-board ground collision avoidance systems

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Keywords

Flight safety, Pilots, Training

Abstract

The goal of the paper is to present an enhancement of the existing on-board ground collision avoidance system (GCAS) that is designed to increase pilot safety in USAF A-10 aircraft. The A-10 is a single-seat, twin-engine aircraft with a 30mm, seven-barreled Gatling gun and 11 weapon pylons designed to fly at low level in close air support missions. The GCAS system provides both visual and aural cues for a pilot-initiated recovery. The proposed algorithm of GCAS enhancement is built on a simple linear regression model that predicts the recovery height of the aircraft following a warning call and allows pilots to compare their own training events with flight test standards. This paper presents a discussion of model development, validation and comparison of the model predictions with actual flight test events. A comparison of recovery techniques and pilot options is included. A series of recommendations and possible usage for Air Force pilot training are also discussed.

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1. Introduction

The A-10 attack aircraft was slated for removal from active inventory, but its superb performance in the operation Desert Storm persuaded the United States Air Force to maintain the A-10 as a front-line weapon system into the twenty-first century. The A-10 is currently undergoing a series of upgrades that will be crucial to increasing overall combat effectiveness, maintainability, and survivability. One of these upgrades is the development of an on-board ground collision avoidance system (GCAS) as an all-weather flight-safety enhancement. The majority of Class A mishaps (involving loss of life or aircraft) occur during training sorties. The GCAS is designed for use during all types of A-10 missions: combat, training and others. While the GCAS is not a low-level terrain guidance system, it does allow pilots to operate effectively at lower altitudes while increasing overall safety.

This paper presents a novel approach to integrate system performance evaluation and pilot training customization. The goal is to develop an enhancement that would allow pilots to compare their own GCAS training events to flight test standards. The proposed algorithm is built on a simple linear regression model that predicts the recovery height of the aircraft following a GCAS warning call and investigates different recovery techniques.

2. System description

The A-10 is a single-seat attack aircraft characterized by a low-wing, low-tail configuration with two high-bypass turbofan engines installed in nacelles extending from the aft fuselage as shown in Figure 1. The A-10 was developed to provide close air support of ground forces fighting in a mechanized battlefield. As a result it is a highly maneuverable, survivable aircraft with long combat endurance. The A-10's primary weapon is a seven-barreled 30mm Gatling gun, which fires at a rate of 3,900 rounds per minute. It also has 11 weapon pylons for carrying a variety of external stores including

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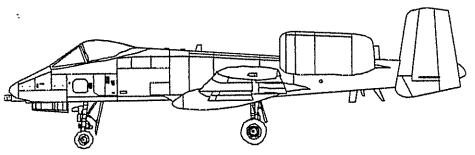
Figure 1 A-10 close air support aircraft



general-purpose bombs, Maverick missiles, forward-firing rockets, and cluster munitions (USAF, 1998).

The onboard navigation system is an embedded GPS/INS (EGI) unit, which is composed of a Honeywell H-764G strapdown inertial navigation system (INS), with a digital ring laser gyro and a Collins GEM-III five-channel military global positioning system (GPS) module. The system obtains GPS signals via a fixed reception pattern antenna (FRPA). A 28-state upper triangular Kalman filter allows for triple navigation solutions: pure inertial, GPS-only, and blended GPS/INS (Honeywell EGI, 1996). The EGI unit is supplemented by a Rockwell radar altimeter that serves as the primary source of altitude above ground level (AGL).

The GCAS system is a function of the low altitude safety and targeting enhancements (LASTE) that drive the aircraft avionics and provides targeting information via a headup display (HUD). GCAS is designed to be a simple warning system that notifies the pilot when its computer algorithm predicts an imminent ground collision. It provides both a visual and an aural warning via a flashing "break X" on the HUD. There are two types of calls: one in which the predictive algorithm (a propriety code of Lockheed Martin) uses navigation information and radar altitude to generate a warning; the other call is simply activated when A-10 descends below an altitude of 90ft (~27.3m) above the ground level. In both cases the ground is assumed to be a level terrain and GCAS is deactivated when the landing gear is extended.

A linear multivariate regression model is formulated based on flight test data from actual GCAS calls and recovery maneuvers. This model would allow both pilots and instructors to characterize GCAS calls and determine validity of the calls. The enhanced GCAS is expected to increase confidence of pilots and improve their reaction and performance. This model also examines the efficacy of different recovery techniques and their impact on total aircraft safety.

3. Flight test data

The 39th Flight Test Squadron (FTS) conducted qualification tests and evaluation of the A-10 GCAS system at Eglin Air Force Base (AFB), Florida, from August 1997 to January 1998. Follow-on testing to system upgrades continues at the present time. A combination of land and water test ranges was used to conduct these flight tests in conjunction with GCAS and other flight test requirements on the same sortie and across a wide spectrum of aircraft weight and performance regimes (EGI QT&E Test Report, 1998).

Flight telemetry was recorded by onboard instrumentation and post-processed by Avionics and Test Analysis Corporation (ATAC) into Excel-based spreadsheet format. All data were generated by use of the special GCAS training mode that induces a 2,000ft (~606m) false ground plane into systems altitude calculations. When in training mode, GCAS assumes that 2,000ft (~606m) AGL is the actual ground level. The data set used in this paper consists of 223 GCAS warning calls on missions flown by six different USAF test pilots.

During GCAS development the system performance requirements, nuisance, good, and late, were based on a flight path angle vs. recovery altitude "funnel" plot. A copy of this plot for all the flight test points can be seen in Figure 2. The lines defining the lower and upper limits of "good" calls are derived empirically and are fixed for this test. The "funnel" is simply understood by considering that the goal of the GCAS system is to prevent controlled flight into terrain (CFIT). For example, if the aircraft is in a steeper dive (i.e. higher negative flight path angle), then the recovery altitude should be higher to achieve the same margin of relative safety as shown in the pictorial representation of GCAS recovery in Figure 3.

Figure 2 Complete GCAS flight test data set

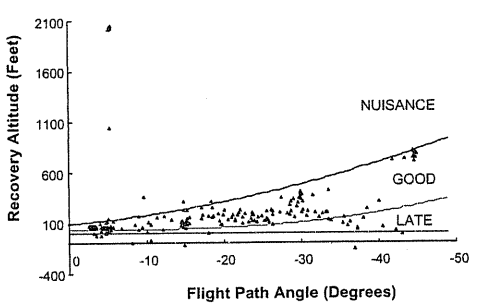


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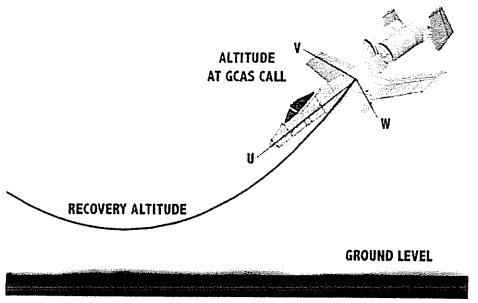
Figure 3 GCAS recovery maneuver



4. Model formulation and validation

In this paper, we have modeled the response of the recovery altitude (that is the dependent variable) as a function of k independent variables. The structure of a multiple linear regression model of the aircraft recovery altitude (AGL) is presented below:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad (1)$$

where y is the dependent variable; $x_j, j = 1, \cdots, k$ are the k independent variables; $\beta_j, j = 0, 1, \cdots, k$ are the regression coefficients; and ε is error term (Hines and Montgomery, 1990). The steps for model formulation are:

(1) selection of the k dependent variables $x_j, j = 1, \cdots, k$ that are of statitstical significance;
(2) identification of the regression coefficients, $\beta_j, j = 0, 1, \cdots, k$ based on flight test data; and
(3) examination of the model accuracy and subsequent revision(s) as necessary.

In this paper, the dependent variable, y, is the aircraft recovery altitude (AGL). The dependent variables, $x_j, j = 1, \cdots, k$ are selected from a variety of flight variables that are available in the test data. An examination of the physical recovery maneuver provides an initial set of dependent variables for the regression analysis. For example, consider an aircraft in a steady decent, during which the following relations hold (Hancock, 1995):

$$T \cos\alpha = D + W \sin\gamma \quad (2)$$

$$L + T \sin\alpha = W \cos\gamma \quad (3)$$

$$M = Tl_T = 0 \quad (4)$$

where the flight path angle γ, angle of attack α, pitch angle θ (where $\theta = \gamma + \alpha$), lift L, thrust T, drag D, and aerodynamic moment M are assumed constant at the instant of observation. However, this is not the case for the basic GCAS problem. The GCAS problem is compounded by two factors: first, the wings may not be level and second, the flight path angle may not be constant.

Let us examine the roll problem first. If the aircraft is maneuvering close to the ground, typical of combat/training sorties, then the aircraft is required to bank (roll) in order to turn. This maneuver brings in an aerodynamic moment that adds an angle term to the above equations. The resulting angular acceleration is commonly referred to as g-loading (defined in terms of the u, v, w airplane coordinate system) and increases the effective angle of attack. Since the bank angle is symmetric and can be either left or right, the absolute value of roll is considered. The second problem is simply that γ may not be constant and that the pilot is varying the pitch angle θ either to stabilize the flight path angle γ (for target tracking) or to position the aircraft for target acquisition. We need to consider the pitch rate to account for this effect. Initially the flight variables listed in Table I were selected to construct a simple linear model.

Owing to instrumentation limitations, lift, weight, thrust, and drag were not available in the data set. However, this limitation proved to be negligible since these variables are highly correlated to airspeed, flight path angle and angle of attack. Also it was important to select only those parameters that are available to the pilot of an aircraft that is not as richly instrumented as a test aircraft. When the GCAS training mode is selected in a standard A-10, immediately after the warning call the standard head-up-display (HUD) symbology is replaced by two pages of aircraft data. While these data are displayed for less than one second, the on-board HUD videocamera records these data for review in the post-flight debriefing. These data pages list the values of

Table I Flight variables as general inputs to the aircraft recovery model

Entry altitude alt_{ent}	Airspeed as
Lift L	Drag D
Weight W	Thrust T
Pitch θ	Pitch rate $\dot{\theta}$
Roll r	Roll rate $\dot{r}$
Flight path angle γ	Angle of attack α
g-loading (u direction) $\ddot{u}$	g-loading (v direction) $\ddot{v}$
g-loading (w direction) $\ddot{w}$	

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over 50 variables such as fuel consumption rate, weapons status, and navigational mode. Inclusion of additional data would increase the model complexity with no significant enhancement of information from the perspectives of model accuracy.

The information provided by LASTE to GCAS is gathered from on-board sensors that may vary in accuracy, reliability and update rate. For example, the α-vane that measures the angle of attack is known to lag the true angle of attack in high α-rate maneuvers. This was determined during an earlier series of flight tests, but α information is included because of its importance in GCAS prediction. Similarly, all other on-board sensors produce noisy signals that induce errors in GCAS information. Let x be the (unknown) true value of a flight variable and let $\hat{x}$ be the estimate of this variable (reported by the measurement filter). If the interaction of multiple noisy sensors is to be considered in the model development, then the multi-covariance between the measurement errors ($\tilde{x} \equiv x - \hat{x}$) must be established. In this paper, all sensor errors are assumed to be unbiased and standard deviations of these errors are assumed small enough to be negligible. The rationale for this simplified model is presented below.

The simplicity of the model allows the pilot to compare his recovery altitude with the model's standard immediately following his training sortie. This addresses two very important issues of flight safety. First it allows the pilot to critique his performance relative to the "standard". This allows the pilot to "customize" the GCAS warning in his mind. If he is consistently performing better than the model then he will develop confidence in his recovery techniques. If his performance is less than the standard but still within the "good" region of the funnel, then he will be able to focus his training for improvement. Most importantly if his performance is both below the standard and the funnel, more flights in different aircraft will be required to determine the reason for the poor performance. This training issue will be examined in more detail later.

In order to generate an initial model, the aforementioned flight variables were gathered from the data set at the time of the warning call. The dependent variable y was determined as the lowest altitude encountered during the maneuver. The parameters listed in Table II were then taken in multivariate linear regression and the initial model was developed. This model was examined with a multivariate fit tool in the SAS statistical software package (Khattree and Dayanand, 1995). Two problems with this model appeared. First, it was obvious that some of the data points from the flight test set were spurious outliers and could be considered for removal from the data set for calculation of the model's coefficients. Second, the summary of fit indicated that the R-squared value (an estimate of the model's accuracy) for this model was 0.8976 and some parameters carried only limited weight, thus could be removed from subsequent models. The next step was to reconsider the physics of the problem and analyze what interactions between flight variables were of importance in the recovery maneuver. These cross-terms were then included in the growing number of overall parameters. The set of model inputs was reduced by using a forward selection procedure, which retains only those variables of 0.500 statistical significance or greater for consideration. This reduced set of 22 model inputs included both original and cross-terms that are listed in Table III. For this model, the R-squared value increased to 0.9790 from 0.8976 and the root mean squared error (RMSE) is reduced to 51.6 feet from 102.8 feet as compared to the initial model in Table II.

Table II Flight variables as initial inputs to the aircraft recovery model

Entry altitude alt_{ent}	Airspeed as
Pitch θ	Pitch rate $\dot{\theta}$
Roll r	Roll rate $\dot{r}$
Flight path angle γ	Angle of attack α
g-loading (u direction) $\ddot{u}$	g-loading (v direction) $\ddot{v}$
g-loading (w direction) $\ddot{w}$	

Table III Flight variables with a minimum of 0.500 statistical significance

Entry altitude alt_{ent}	Airspeed as
Pitch θ	Pitch rate $\dot{\theta}$
Roll r	Angle of attack α
Flight path angle γ	g-loading (v direction) $\ddot{v}$
g-loading (u direction) $\ddot{u}$	g-loading (w direction) $\ddot{w}$
$\gamma \times as$	$\gamma \times \lvert r \rvert$
$\gamma \times alt_{ent}$	$\theta \times \lvert r \rvert$
$\alpha \times alt_{ent}$	$\lvert r \rvert \times alt_{ent}$
$\alpha \times as$	$\alpha \times u$
$\lvert r \rvert \times as$	$\alpha \times v$
$as \times alt_{ent}$	$\alpha \times w$

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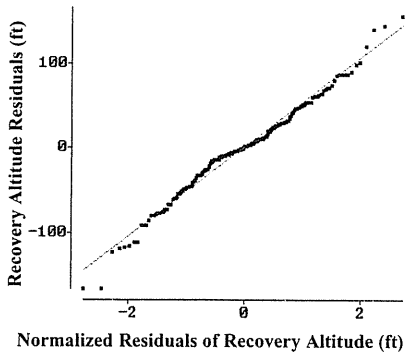
Although the model with 22 parameters has a high level of accuracy, the inclusion of all these variables complicates the model and makes it more difficult to use. In order to simplify the model both in calculation and in actual use, some parameters need to be removed. In a similar forward selection method, those parameters with the least statistical significance were removed first and the effects on the model were re-examined. The objective was to reduce the number of parameters without compromising the statistical significance of the model. The number of regression variables was reduced to a total of ten comprising nine flight variables as seen in Table IV.

A split sample technique was used to validate the model with the above flight variables as inputs. In this technique, the sample runs were randomly divided into the control group and the test group. Multivariate regression analysis of the control group yielded a model consisting of the same parameters as the proposed final model but with slightly different regression coefficients β_js. When compared to the proposed final model, the test model showed only slight differences in β_js and the differences in R-squared and RMSE were statistically insignificant. This indicated that the model was indeed valid for the range of the included flight variables. After validating the model the data were examined for spurious calls that might unnecessarily skew the β_js. The normal quantile-quantile (Q-Q) plot method was used to identify the *outlier* data points that were rejected in calculation of the final model. Since certain quantiles approximately follow a chi-square distribution for multivariate normal data, the empirical quantiles from these data are then plotted against the theoretical quantile in a normal Q-Q plot. If the assumption of normal distribution is valid, then the Q-Q plot should be a close fit to a straight line passing through the origin (Khattree and Dayanand, 1995). If only a few points on a Q-Q plot fall outside the region covered by the majority of points then those points are suspected outliers. Figure 4

Table IV Flight variables as final inputs to the aircraft recovery model

Entry altitude alt_{ent}	Pitch rate $\dot{\theta}$
Pitch θ	Roll r
g-loading (u direction) $\ddot{u}$	g-loading (w direction) $\ddot{w}$
$\gamma \times alt_{ent}$	$\lvert r \rvert \times alt_{ent}$
$\alpha \times alt_{ent}$	$\alpha \times as$

Figure 4 Normal Q-Q plot



shows the normal Q-Q plot after removal of five obvious outliers that are statistically insignificant with respect to the total data set. The model yields the following equation:

$$\begin{aligned} alt_{rec} &= -144.65 + 1.0486 alt_{ent} \\ &+ 370.197\theta + 0.2604\gamma \times alt_{ent} \\ &+ 6.13494\ddot{u} + 108.78\dot{\theta} - 0.5417\alpha \\ &\times alt_{ent} - 0.1203r \times alt_{ent} + 6.8345\alpha \\ &\times as + 1.4939\ddot{w} + 202.382r. \end{aligned} \tag{5}$$

The above model was used to generate predicted recovery altitudes that were, in turn, compared to the actual flight test data points as seen in Figure 5. The model predictions are consistent and unbiased with a standard deviation of 51.75ft (15.7m). This model assumes that the initial parameters are normally distributed which allows the model to accurately predict other points within the given range. Both the normal Q-Q plot and the residual plot confirm validity of this assumption.

Ultimately this model is presented for subjective evaluation based on the comparison between model and actual test points in the funnel plot as shown in Figure 6. It appears from this plot that the model is better at predicting stable entry conditions than relatively more transient conditions. The two dense groupings at –5, –15, –30, and –45 degrees were

Figure 5 Model and flight test data comparison

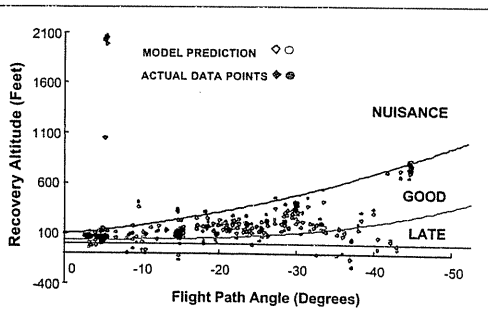


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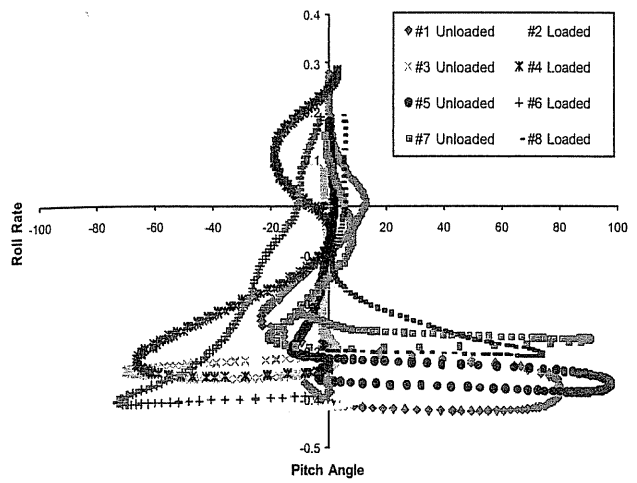
Figure 6 Bivariate plot of roll rate versus pitch angle



wings-level dives, an entry condition that allows the test pilots to be more consistent from run to run than a high bank entry.

The above observation lends understanding to some of the limitations of this model. This model is only valid for the range of parameters over which the model was generated. It would be ill-advised to use this model for extrapolation of GCAS events beyond the range of parameters shown in Figure 4. Additionally this model does not apply to non-standard recovery techniques or unusual aircraft attitudes. There are errors in the model from both sensor inaccuracies (noise and bias) and model over-simplification. For its intended purpose as a training aid these errors should not impact its use. It is important to recognize that the model accuracy is limited and should not be relied upon as the sole source of GCAS evaluation.

5. Pilot and aircraft performance

The primary goal of GCAS is to make the A-10 safer for the pilot in all flight regimes. However, GCAS in the A-10 is still primarily a function of the pilot's capabilities since he is the sole manipulator of the flight controls. There are three identifiable regions of flight with which the pilot must be familiar in order to maximize the safety characteristics of the GCAS system. First, the pilot must be aware of what basic flight maneuvers he is performing and at what altitude. This is a simple concept since every pilot, no matter what aircraft he is flying, needs to be aware of his relative position to the ground. These conditions will be named the pre-call conditions. Next are the conditions at the call and the pilot's recognition that a GCAS call has been issued. Finally the pilot initiates a recovery maneuver which terminates in a successful recovery (USAF Test Pilot School Class Notes, 1996).

We will examine each of these three areas. In the pre-call conditions there exists a significant difference between training and combat. First in training the pilot is expecting a GCAS warning call and so is mentally prepared to react. There are some training methods to help the pilot simulate a distracted mental condition but nothing can truly simulate the shock of an unexpected GCAS call. This is why nuisance calls are detrimental to the overall effectiveness of the system. Examine for a moment the group of nuisance calls at –5 degrees and 2,000ft AGL as seen in Figure 5. The pilot who receives these calls is inclined to ignore them because this is a low threat flight regime. If he is aware of this situation, he knows instantly that he is in no immediate danger. If this occurs too often either in the GCAS training mode or the standard mode during actual flights then the pilot will become conditioned to ignore this GCAS call. The danger occurs when the pilot is distracted or confused about his position and ignores a call because it is "just another nuisance call" when in fact it is a valid call.

The pilot who is aware of his situation and is operating in a high probability of call regime will expect a call. This is where the advantages of having a model to compare GCAS training with come into play. If the pilot is aware of his situation and is prepared to execute a maximum performance then he may be able to stay on flight path just a bit longer, giving him time to complete a strafing or bombing run. Initially this seems more dangerous than breaking off the run and trying it again. However, in reality, it turns out to be safer since the risks of just getting a bombing run on target in a combat situation are high and if the pilot can eliminate a return flight he is reducing the total risk to himself and his fellow pilots.

In the second area, the warning call regime, the primary concern is identification of the GCAS call. A pilot who is positionally aware should recognize that a call has been made and begin the appropriate recovery maneuver. When this is not the case, the pilot may either not initially recognize that a call has been made or he may be unaware of the aircraft's orientation. In either of these cases it is

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imperative that the pilot assume the validity of the call and rely on proven methods of establishing orientation. The combination of an unexpected call and an unusual aircraft attitude dramatically reduces the small tolerance for human error designed into the GCAS warning system. The only way to address this situation is through increased training.

The recovery phase is characterized by the technique employed by the pilot to transition the aircraft from its current negative flight path angle to a positive angle. For a normal wings-level dive, the recovery maneuver is simple and straightforward: smoothly apply full back stick pressure. In inverted level dives the only difference is that forward stick pressure is required to initiate a climb. Once the bank angle increases beyond 15 degrees of bank successful recovery methods vary.

During flight testing of the A-10 at Eglin AFB the effect of different recovery methods on the final altitude was a controversial issue between test pilots and flight test engineers. A set of eight runs was compiled at bank angle with two different recovery methods. Owing to constraints in the flight test program, in-depth analysis of the differences was left unfinished. With the simple model developed in this project it was possible to examine the different recovery techniques. The first technique is a more conservative method in which the pilot applies full opposite aileron to roll the aircraft to a wings-level position and then use back stick pressure to recover from the dive. This technique minimizes load factor and is consistently reliable. The second technique is to simultaneously roll and pitch at the same time. This is called a loaded roll, and increases the load factor on the aircraft.

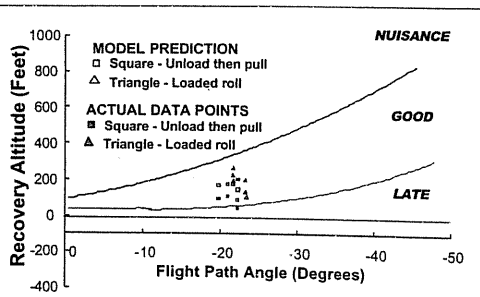
Figure 6 shows a family of roll rate versus pitch angle plots representing four samples each in loaded and unloaded recovery techniques. The unloaded recovery in Case #5 results from the dynamic sequence of pure roll followed by a change in pitch. By contrast, Case #6 illustrates a loaded roll recovery in which both roll and pitch elements are simultaneously present. Other samples in the data set are less clearly identifiable as loaded or unloaded recoveries. The plots in Figure 6 show that both loaded and unloaded cases undergo a high roll rate and that the pilot attempted to fly two significantly different recovery techniques. However, the actual aircraft dynamics represent a range of recovery performance spanning the extremes shown in Cases #5 and #6. Figure 6 suggests that the actual recovery altitudes would be distributed across a similar spectrum, and raise the question of how the recovery altitude is affected by the differences between the two recovery techniques.

Figure 7 shows a funnel plot of all 60 degree bank runs, comparing the loaded and unloaded recovery techniques, along with both model and actual flight test data that are obtained from the recovery plots in Figure 7. The flight test data in Figure 7 indicate that the loaded recovery technique generates higher and thus safer recovery altitudes. While the flight test data tend to prefer loaded recovery in agreement with the test pilots' opinion, the model data may not specifically indicate a preferred recovery technique because the difference between the two techniques is not significant. A possible explanation of this phenomenon is that the pilot was more aggressive during flight test in recovering the aircraft with the loaded roll. This could result from the physiological effects of increased aircraft load factors on the pilot. At this stage, owing to limited flight test data, the model credibility is not completely established as the difference in recovery heights is within the error margins of the model. Therefore, each pilot should be aware of the model limitations and compare the different methods for himself.

6. Summary, conclusions and future work

The objective of this work presented in this paper is to provide a means of enhancing the on-board ground collision avoidance system (GCAS) in order to increase overall pilot safety. The paper presents a predictive model that allows the pilot to readily compare his performance with the established flight test standard. This multivariate linear regression model is formulated based on the physical equations of motion, and test data of flight

Figure 7 Comparison of 60 degree bank recovery methods



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variables on A-10 aircraft. The model output is aircraft recovery altitude and the model input consists of a set of ten regression variables including nine flight variables. These regression variables were validated by the random split sample technique and the regression coefficients were identified from the actual flight test data.

The model has been used to test the loaded and unloaded roll recovery methods for responding to a GCAS warning call at large bank angles. Although no definite conclusions could be derived on superiority of one specific recovery technique due to limited flight test data, the loaded roll method appears to yield a higher recovery altitude and thus should be examined by the pilot during GCAS training. Since most Air Force pilots are not trained as engineers, it is important that any training aids be conceptually understandable to them. Without a model to compare their training runs, pilots are forced to measure their performance on crude system acceptability standards. With this model and improved understanding of the GCAS system the pilot training methods can be individually tailored to maximize the effectiveness of training. The pilot desiring quick training customization can analyze any unanticipated GCAS call on site.

In light of the work presented in this paper several important recommendations would further enhance the overall flight safety. Since flight tests are limited, the number of samples used in creating this model are relatively small compared with the total number of GCAS events conducted Air Force-wide. A centralized database of all GCAS training events compiled by USAF pilots would be enormously beneficial for model refinement. This could be developed into an Air Force-wide decision support system. A basic personal computer installed in each A-10 squadron connected to the database could give a pilot instant access to track his performance over time, in particular aircraft, or with specific types of recovery maneuvers. This knowledge would prove extremely beneficial in combat situations where a recovery maneuver, unnecessarily initiated too early, results in a repeated attack run and increased risk. It should be noted that the model presented in this paper enhances pilot safety and is not a substitute for the GCAS algorithm.

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Glossary

AFB	Air Force Base
AGL	Above ground level
CFIT	Controlled flight into terrain
EGI	Embedded GPS/INS
FRPA	Fixed reception pattern antenna
FTS	Flight test squadron
GCAS	Ground collision avoidance system
GPS	Global positioning system
HUD	Head up display
INS	Inertial navigation system
LASTE	Low altitude safety and targeting enhancements
RMSE	Root mean square error

Nomenclature

α	Angle of attack
γ	Flight path angle
ε	Error term
θ	Pitch
$\dot{}$	First time derivative
$\ddot{}$	Second time derivative
alt_{ent}	Entry altitude
alt_{rec}	Recovery altitude
as	Airspeed
D	Drag
$E(x)$	Expected value of x
L	Lift
l_T	Distance from thrust point to center of mass
M	Aerodynamic moment
r	Roll angle
T	Thrust
u	Displacement in u-direction
v	Displacement in v-direction
w	Displacement in w-direction
W	Weight