Surrogate UAV Approach and Landing Testing – Improving Flight Test Efficiency and Safety

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ABSTRACT

For the past two decades Calspan Corporation has been extensively involved in UAV development programs through the use of the company's variable stability in-flight simulators. The variable stability in-flight simulators are ideally suited for use as manned UAV surrogates as they can simulate the UAV's bare airframe aerodynamics and inner loop control laws as well as the many outer loop auto-pilots being developed. These test programs have included numerous autonomous landing projects for traditional UAVs and spacecraft re-entry vehicles as well as autonomous air refueling programs and collision avoidance programs for UAVs. The surrogate UAV allows for very high fidelity and cost effective testing without most of the risks inherent to UAV flight test. Surrogate UAV flight testing is not without pitfalls however, and the purpose of this paper is to present some of the lessons learned from previous testing and introduce methods to improve safety and efficiency when using a manned surrogate.

Figure 1: Learjet Surrogate Flying Autonomous Formation with KC-135

1.0 INTRODUCTION

Calspan has operated its variable stability in-flight simulator aircraft as manned UAV surrogates for many years. The advantages of using a manned surrogate are obvious. All the constraints that apply to operating a UAV are instantly avoided. Special use airspace and special operating rules are not required. The surrogate can takeoff, land, and fly in traditional airspace following FAA and ATC rules. There is no lengthy flight certification process as the UAV algorithms are not flight critical in a manned surrogate. The same automatic safety trips that protect the Calspan in-flight simulators from a bad evaluation pilot input will protect them from a bad UAV control input. Safety and efficiency are greatly increased by using a surrogate. By using a variable stability manned surrogate, the fidelity of the results is extremely high. So long as the aero-model of the target UAV is known, the variable stability can provide a perfect replication of what the UAV behavior will be at essentially zero risk and significantly improved efficiency and reduced cost. However, there are some pitfalls to be aware of when employing a manned surrogate. Most significantly, there are no built in protections in any manned surrogate currently flying that will protect the surrogate from a midair collision or a hard landing. It falls upon the Safety Pilot in the surrogate aircraft to avoid these mishaps. The purpose of this paper is to introduce the reader to the role of the Safety Pilot, what that Safety Pilot needs in order to effectively perform his/her duties, and the concept of Available Reaction Time (ART) as an indicator of how successful the Safety pilot can be in doing that job. In a previous paper presented to the Society of Experimental Test Pilots (SETP) this concept was illustrated using an up and away scenario where a midair collision was the dominant risk. This paper will look specifically at the landing case and how to ensure the Safety Pilot can safely protect the surrogate when on an approach to landing. These principles apply not only to surrogate UAV operations but any landing case where a Safety Pilot is providing the safety during the landing phase.

2.0 SAFETY PILOT ROLE

It is important to recognize and protect the Safety Pilot's role in surrogate mishap prevention. When flight testing the actual UAV, risk is reduced through lengthy flight worthiness procedures and testing. This testing can be extremely costly and time consuming and, history has shown, not at all fool proof. Mishaps among new UAV designs are orders of magnitude higher than similar manned aircraft and first flights of any aircraft are significantly more dangerous than flying a tried and proven surrogate. By using the surrogate we avoid the need for such lengthy and costly testing for it is the Safety Pilot that provides all the safety needed in a surrogate flight test. The Safety Pilot cannot do this, however, unless he has the ability to do so. A Safety Pilot must be able to OBSERVE the system performance, IDENTIFY when the UAV controller is creating a hazardous condition, DISENGAGE the UAV controller from the surrogate and take over manually, and finally must MANEUVER the surrogate to safety. Additionally, the Safety Pilot must have adequate time to do all these things. If the safety pilot first becomes aware that a dangerous condition exists after it is too late to recover, the Safety Pilot cannot provide the protection required. We use the concept of Available Reaction Time (ART) to determine if sufficient time is available for the Safety Pilot to react. Each of these five elements will be discussed briefly now and then the ART principle will be used to evaluate the special case of a surrogate landing test.

Figure 2: Learjet Variable Stability manned UAV Surrogate in formation with C-12 Tanker Surrogate during Project “No Gyro” Test Program

2.1 Observe

Observe UAV System Performance: The surrogate Safety Pilot must be able to observe the UAV operations being conducted. This may seem obvious, after all, the Safety Pilot is in the surrogate, how can he not be able to observe what is going on? As obvious as it sounds, it is often a problem that must not be ignored. A couple examples might help illustrate the problem. During an autonomous air refueling test, the Learjet surrogate was programmed to fly several station keeping and contact positions. Since the Learjet Safety Pilot sits on the left side of the Learjet, is was easy to monitor the UAV performance when on the right side of the tanker but when station keeping on the left side, the Safety Pilot had to observe the operation cross-cockpit. At times making it nearly impossible to see the tanker. If the Safety Pilot cannot see the tanker, he cannot observe how well the UAV is flying formation with it. Likewise, during the rejoin to the pre-contact position, the UAV was programmed to rejoin from a very low position. While ideal for a UAV, it made it nearly impossible for the Safety Pilot to see the tanker. Also consider sun angle and neck fatigue when planning a surrogate operation as a bad sun angle could ruin the Safety Pilot’s view of any operation.

2.2 Identify

Identify Deviations from Normal: In order to determine when the UAV system is not performing satisfactorily, the Safety Pilot must know what normal is and also must have a way of identifying deviations. Safety Pilots must be aware of the design mechanization and mode logic of the UAV so that they can properly diagnose unusual behavior. Likewise, they must have a metric to use to identify when a malfunctioning UAV has gone too far. When margins are small, the criteria must be clearly defined and easily recognized. When margins are large, more relaxed criteria can be used. The amount of margin available is evaluated using the Available Reaction Time analysis we will discuss shortly.

2.3 Disengage

It is absolutely critical that the Safety Pilot have an intuitive, redundant, and reliable method of disengaging UAV control and taking over manually. The potential ramifications of a runaway UAV that cannot be disconnected are obvious so all methods of disengaging automatic control must be tested thoroughly whether they are manual or automatic disengage methods.

2.4 Maneuver

Maneuver to Safety: After disengage, the Safety Pilot must be able to maneuver to safety. Consideration should be given to maneuver stability, speed stability and trim of the surrogate at disengage. Taking over control of a badly out of trim surrogate may be extremely dangerous so trim should be monitored in some way while under automatic control.

3.0 AVAILABLE REACTION TIME (ART)

In addition to the four items mentioned above, the Safety Pilot must actually have the time to do them prior to a mishap occurring. The concept of ART emerged during Automatic Ground Collision Avoidance System (Auto GCAS) testing. During these tests, intentional collision geometries were created to allow the automatic system to recover the aircraft prior to ground impact. What if the Auto GCAS failed to operate? There still must be sufficient time for the test pilot to recognize the failure and recover manually. A buffer altitude was added to the terrain that would ensure that Safety Pilot had the time to do just that. Computing that buffer altitude was difficult as steep high speed runs obviously demanded larger buffers than shallow low speed runs. The concept of ART was used to ensure that, no matter what the collision geometry, a buffer altitude would be used that provided adequate time for the test pilot to recognize a failure and still recover to avoid ground impact. Figure 3 illustrates the ART concept.

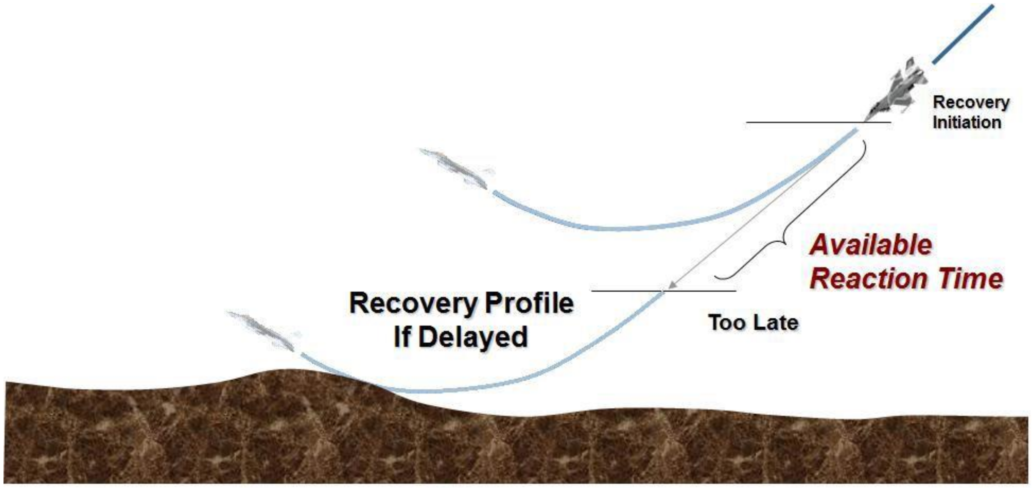

Figure 3: Available Reaction Time Illustration

To compute the ART, the planned recovery is modeled first with no delay. If no ground collision occurs, the recovery is delayed a short period of time and the recovery is then modeled again. If ground impact is averted, a larger delay is used and the process continues until a delay is big enough to cause the recovery to just touch the ground. That delay is the ART. It represents how long the pilot can delay the recovery and still not impact the ground. Test runs with small ART are risky while runs with very high ARTs are low risk. If a run was deemed too risky, the buffer altitude and abort conditions would be raised until the ART was acceptable. For Auto GCAS testing, four seconds or more was considered low risk and no runs under 1.5 seconds were allowed.

Figure 4: Learjet Surrogate UAV Flown Remotely to Landing with a Two Second Datalink Delay

3.1 ART Landing Example

Let's assume we've been tasked to simulate the landing behavior of a UAV using the Calspan Learjet Surrogate UAV. We begin by looking at each potential hazard with respect to the five elements described above. The risks involved in the landing phase include: hard landing, off-field landing, stall, wing strike, and excessive side loads on gear. In all these cases, the Safety Pilot is able to observe system performance, identify deviations from normal and disengage and maneuver to safety. The issue at hand, however, is whether the Safety Pilot can do that within a reasonable Available Reaction Time? To do this analysis we begin with the event that causes these hazards to occur. A normally operating UAV controller will not cause any problems so we are actually interested in possible failure states. For surrogate UAV operations we need not concern ourselves with why a failure would occur but simply assume it will. Note that this a distinct difference in philosophy between surrogate operations and actual UAV operations. In an actual UAV flight test, safety resides in the UAV itself. This is why a systems safety expert will examine and evaluate every possible failure mode and asses the risk of each of those events occurring. In surrogate operations, safety lies with the Safety Pilot so we simply assume the worst case event will occur and ask ourselves if the Safety Pilot can protect the surrogate given that event. Regardless of why the failure occurs, the failure will manifest in the surrogate as an improper aircraft response. If the improper response occurs slowly (slow-over failure), the Safety pilot will see the surrogate slowly deviating from desired trajectory and can easily disengage before the situation deteriorates too badly. For example, a UAV controller that pitches the aircraft up on final vice holding glide path will be obvious and the Safety Pilot will have plenty of time to disengage prior to reaching a stall condition or other unfavorable attitude. The real problem is the rapid failure. A hard-over control input that immediately brings the aircraft to a stall or other unusual attitude will seriously tax the Safety Pilot's reaction time. Hard-over failures are quite common in surrogate UAV testing. A mode change that has a sign error, for example, will quickly go hard-over as the UAV attempts to use more and more reverse input to correct. In fact, almost all failures under closed loop control tend to result in a hard-over condition as the UAV attempts to correct the ever worsening condition with an ever larger bad control. So it is the hard-over type failures that dominate our risk analysis for surrogate operations. Fortunately, the Learjet UAV surrogate has some built in protections for hard over inputs so we do not necessarily have to assume the absolute biggest and quickest bad input. These protections are platform specific so different thresholds will apply if using a different surrogate. In the Learjet surrogate, there are three automatic safety trips that will prevent a hard over from occurring. These trips are designed to prevent hard overs but also to limit the hinge moments on the control surfaces to protect the aircraft structure. Suffice it to say, that if a large step hard-over were to be commanded, the automatic safety trips would disengage the controller and return control to the pilot prior to the aircraft responding with any significant motion. The problem for the Learjet then is the small hard over or quick ramp input. These events will not trigger a safety trip and it will be up to the Safety Pilot to manually disengage the controller. The obvious next step then is to identify what is the worst case UAV controller response that will not cause an automatic safety trip. Once this event is identified, each of the above hazards can be evaluated for ART. For the Learjet, most of this testing was done in the flying qualities simulator at the USAF Test Pilot School. The details of the entire simulator test matrix will not be delved in here, but suffice it to say, only one condition presented a problem in terms of pilot reaction time and that was the hard landing case. For all other hazards, the ART was sufficient such that an attentive Safety Pilot would have no problem recognizing and recovering prior to any danger. The hard landing case on the other hand had a very small ART. In other words, by the time the Safety Pilot recognized that the worst case nose down event had occurred, he would already be too late to prevent a hard and early landing.

If the worst case nose down event does occur, the Safety Pilot will have to react and then recover the surrogate to a climb or level flight prior to impacting the ground. Since the surrogate is on final approach for landing and already in a descent, some altitude loss will always occur prior to reaching level flight. When we evaluate any landing for this event, three phases will emerge. Early in the approach, the surrogate is so high that the safety pilot will be able to recover (after an acceptable reaction delay) to level flight before getting near the ground. Late in the approach the surrogate will be so close to touch down, that the pushover will simply expedite the landing but the ground will stop any continued descent. It is the middle of the approach that presents a concern. At some point in the approach, the amount of altitude lost in the recovery will exceed the height of the surrogate above the ground and an early and possibly hard touchdown will occur. This is the "red zone threshold" line in Figure 5. At any point below that altitude an early touchdown cannot be prevented. That early touchdown will occur within the hard-over footprint shown in the figure.

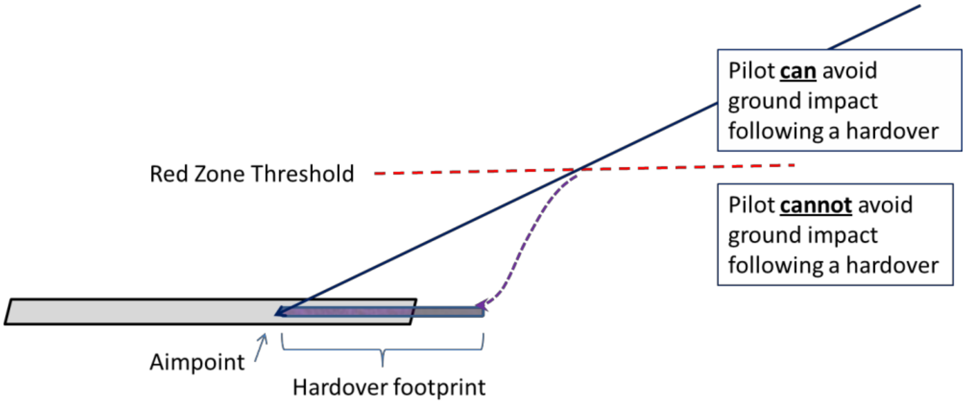

Figure 5: Landing Approach Phases

This creates two dangerous outcomes that must be mitigated. The first is the potential for an off-field landing short of the prepared surface. The second danger is a hard landing that exceeds the structural strength of the surrogate's landing gear. The first danger is actually quite easy to mitigate. By adjusting the aimpoint of the planned approach, we can move the hard-over footprint. If any part of the hard-over footprint lies on an un-landable surface, the aimpoint can simply be shifted so that the entire footprint lies over a landable surface whether that be runway or overrun or even a suitable lakebed extension. Figure 6 illustrates a footprint analysis that was done by a contractor in support of a USAF TPS auto-land test. In that example you can see that the hard-over footprint is as much as 1000 feet short of the runway. It was a simple matter to then set an aimpoint that was at least 1000 feet long of the first usable portion of the runway. As long as the runway is long enough and a proper aimpoint is chosen, a short off-field landing should never be a concern.

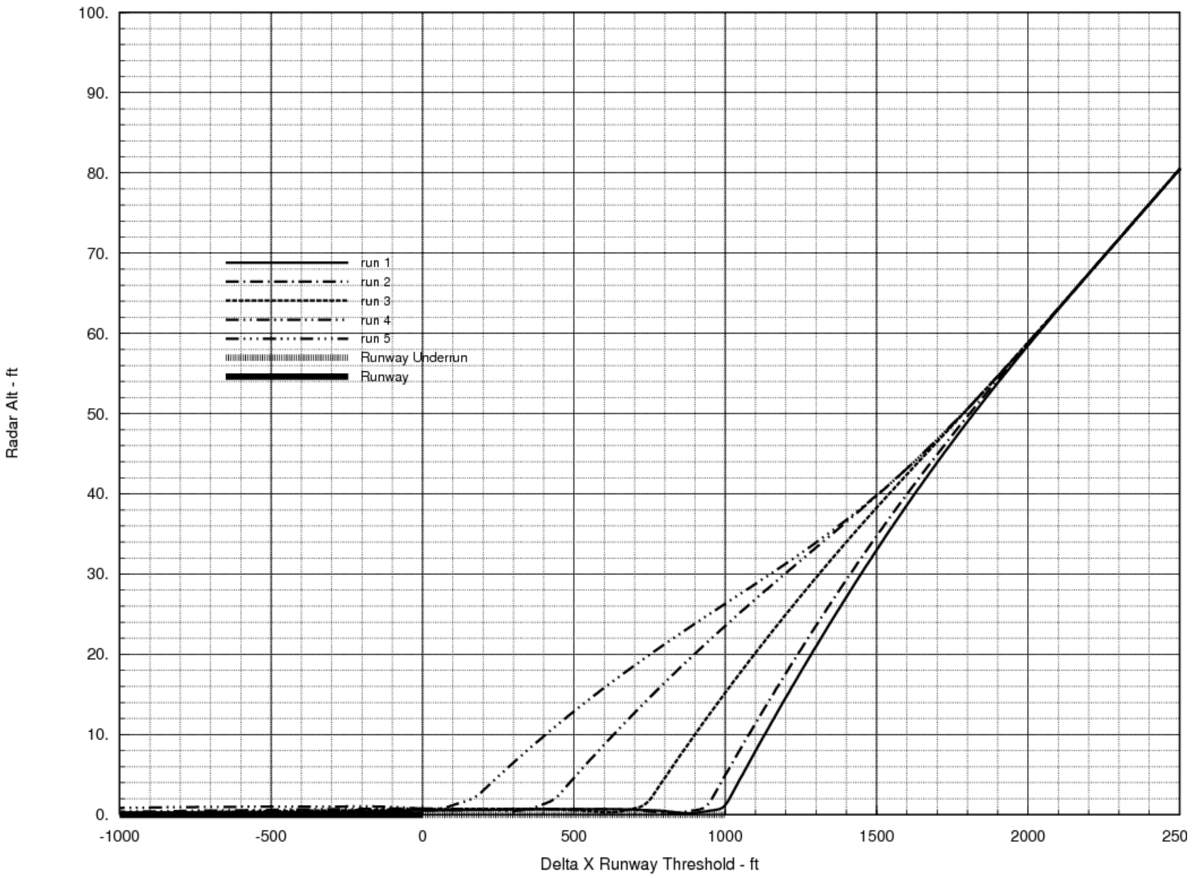

Figure 6: Example of a Hardover Footprint Evaluation

The remaining problem of a potential hard landing is a bit more complicated to evaluate. The first thing to do is to identify the Red Zone. Figure 7 shows a simulator evaluation used to determine the Red Zone for a Learjet surrogate flight test. A three degree approach was planned so the simulation began with a slightly steep (worst case) 3.5 deg degree approach. The blue line represents the elevator position and you can see that, at around 25.5 seconds into the run, a step input occurs that is just shy of the safety trip threshold. The pilot reacts in just under a second (our desired ART) and reverses the input. The surrogate loses about 38 feet during this event. With this information we can set 50 feet as our Red Zone altitude. Above 50 feet, the Safety Pilot has adequate reaction time to keep the surrogate from touching the ground following a worst case nose down hard-over. Below 50 feet, the surrogate may touchdown early. If we apply proper aimpoint control, an early touchdown is not a problem but a firm one is. The Red Zone Threshold is an important parameter for safety build down and risk mitigation. Above 50 feet, there is essentially zero risk for any potential failure mode. This means there is no additional safety value in first doing a build down above 50 feet. For example, on one landing test, prior to the development of these principles, a build down plan of 500 feet, 200 feet, 100 feet, 50 feet, and 20 feet were applied prior to the actual attempted landing. Since the risk above 50 feet is essentially zero, we find that the 500, 200, and 100 foot build down steps were not necessary. Likewise, the 20 foot build down had all the risk of the actual landing but not the technical benefit. All of those steps could have been replaced with a single 50 foot build-down test.

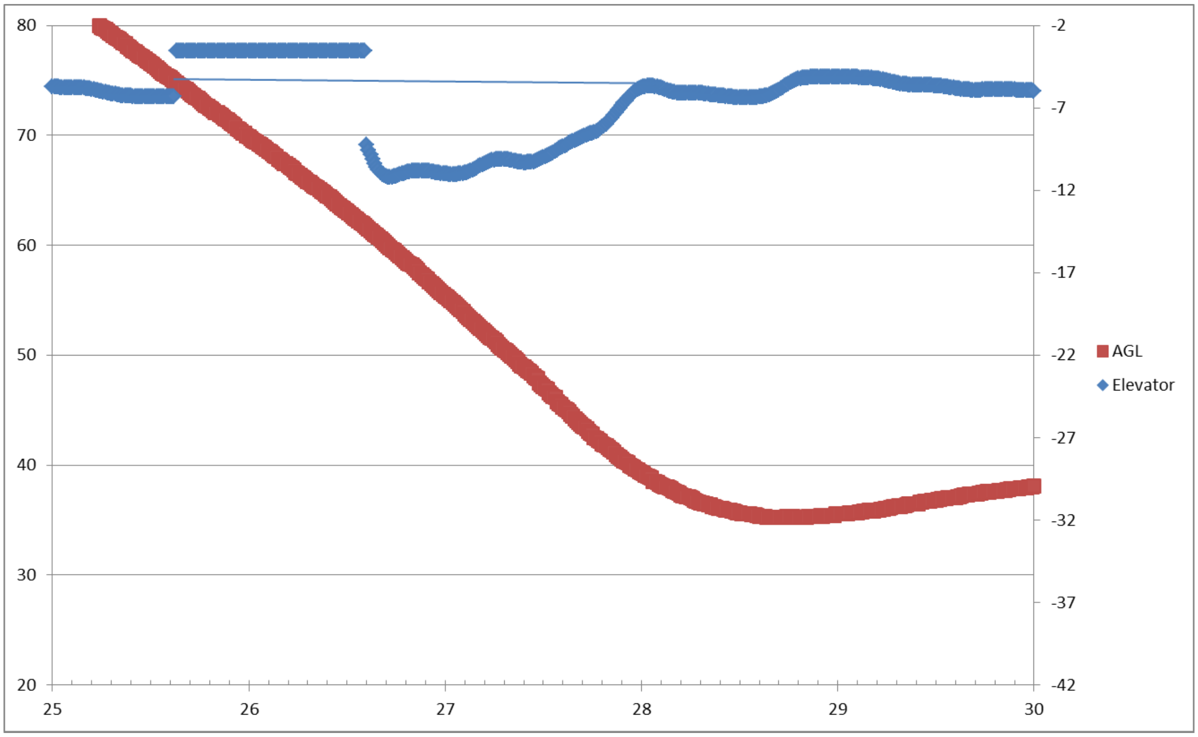

Figure 7: Hardover Evaluation during Learjet Three Degree Approach

Once the Red Zone Threshold is identified, the severity of the risk below that altitude has to be evaluated. To do this, we apply the same worst case hard-over and look at the peak vertical velocity prior to the Safety Pilot recovering. We used a one second pilot reaction time as the minimum required for this type of testing and found that gear loads would be exceeded with significantly less than one second of pilot reaction time. There are three approaches that could be taken to address this. First we can hope the Safety Pilot reacts faster and accept the risk of mishap. This approach is a bit foolish as something always seems to go wrong at some point in surrogate testing. The second method is to restrict the UAVs ability to maneuver as aggressively. In other words, shrink the worst case maneuver in some way. This could be done with more restrictive automatic safety trips or some form of software limit on the UAV controller's ability to maneuver. These limits must obviously be proven reliable prior to executing the test. This was the method chosen for the TPS auto-land test. The previous paper on topic describing surrogate UAV operations in the air refueling context described how limiting surrogate performance could yield the required ART[1]. The final method of mitigating the risk is procedural which we will describe here.

If you look closely at Figure 7, you may notice an interesting characteristic of the recovery. Note the slope of the altitude trace. You will notice that the rate of descent increases considerably even after the Safety Pilot reacts and begins the recovery. The peak vertical descent occurs late in the recovery not when the Safety Pilot first recognizes the event and begins the recovery. If we look closely at Figure 6 we will see that a failure right at the beginning of the red zone creates a significant vertical descent but a failure later in the approach does not. The reason that this happens is the surrogate flight conditions are not static during the approach. At some

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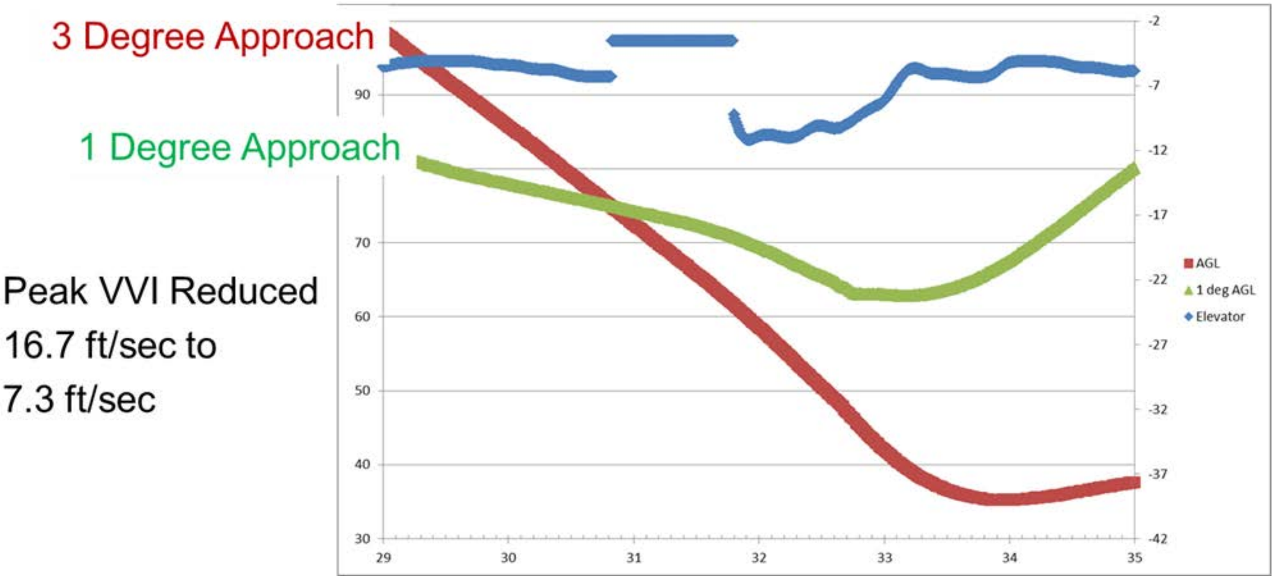
[1] The previous paper titled "Lower Risk Surrogate UAV Flight Testing Lessons Learned from a UAV 'Instructor' Pilot" is available online at setp.org

point the surrogate will begin a round out and flare prior to touch down. What these two plots tell us is that the maximum risk is when we first enter the red zone not while we are fully in it. At some point in the approach, the surrogate will be nearly level and no longer on a three degree approach and the severity of a hard-over will be much less. We did our original analysis from a 3.5 deg approach which already has a considerable descent prior to the simulated failure and results in a descent rate that can exceed structural limits but what about the end of the flare? If a portion of the peak vertical descent comes from the initial conditions, it follows that if we fly a shallower approach, the peak descent following a failure will not be as severe because the failure begins with a smaller descent. Figure 8 below compares a failure on three degree approach with a failure on a one degree approach.


3 Degree Approach

1 Degree Approach

Peak VVI Reduced
16.7 ft/sec to
7.3 ft/sec

Figure 8: One Degree versus Three Degree Approach

Note that the total altitude loss with a one degree approach is reduced from 38 feet to about 12 feet. In effect we lowered our Red Zone Threshold to one fourth of the original. Additionally, the peak vertical descent was reduced from 16.7ft/sec which exceeds gear limits to 7.3 ft/sec which is hard but survivable. These facts bring to light a potential procedural way to mitigate the hard landing risk and the technique used on the most recent Test Pilot School test program flown in the Learjet. Above the 50 foot Red Zone Threshold, a three degree approach can be flown as is normally done. When the surrogate reaches 50 feet and prior to the red zone for the three degree approach, the UAV operator (if remotely controlled) or auto-pilot will begin to shallow the approach angle so as to be stable at a one degree or less glidepath by 12 feet which is the red zone altitude for a one degree approach. That shallower glidepath is then held until flare/touchdown. By using this procedure, we effectively shrink the Red Zone prior to entering it until we reach a Red Zone that will not exceed the gear limits. Any failure at any point in the approach will allow us to prevent a hard landing while maintaining a minimum of one second ART.

4.0 SUMMARY

As you have seen, the fundamental distinction between surrogate UAV flight test and UAV flight test is the role of the Safety Pilot. Safety is provided solely by the Safety Pilot in surrogate UAV testing which adds immensely to test efficiency and safety. However, we must respect the Safety Pilot's role and ensure that the Safety Pilot can OBSERVE, DETECT, DISENGAGE, and MANUEVER the surrogate to safety within a reasonable reaction time. We do not concern ourselves with how a failure could occur and simply assume the worst case event will occur and then go about ensuring that the Safety Pilot can react in time to prevent any bad occurrence from happening. When that is not the case, we need to reduce the severity of the worst case event, or apply procedural mitigations to ensure the worst case event will not present a hazard within the required pilot reaction time.