A PLAN FOR ADVANCED GUIDANCE AND CONTROL TECHNOLOGY FOR 2ND GENERATION REUSABLE LAUNCH VEHICLES

John M. Hanson
Aerospace Engineer, NASA Marshall Space Flight Center, Huntsville, AL

Abstract

Advanced guidance and control (AG&C) technologies are critical for meeting safety/reliability and cost requirements for the next generation of reusable launch vehicle (RLV). This becomes clear upon examining the number of expendable launch vehicle failures in the recent past where AG&C technologies would have saved a RLV with the same failure mode, the additional vehicle problems where this technology applies, and the costs associated with mission design with or without all these failure issues. The state-of-the-art in guidance and control technology, as well as in computing technology, is at the point where we can look to the possibility of being able to safely return a RLV in any situation where it can physically be recovered. This paper outlines reasons for AG&C, current technology efforts, and the additional work needed for making this goal a reality.

Introduction

Currently-demonstrated guidance and control technologies are able to automatically fly a reusable launch vehicle to orbit and back to a safe landing. The Space Shuttle has demonstrated this well over 100 times. The guidance and control for the Shuttle is automated except for the approach and landing phase[1,2,3]. Although the astronauts fly the Shuttle during the final phase of flight, an automated system is available[4]. The Shuttle also has the capability to successfully abort for a number of situations where (single or multiple) main engines are shut down during flight[5]. Planning for each abort situation (time of engine loss, number of engines lost) requires a significant amount of ground analysis, including designing abort trajectories, capability charts, dump scenarios and certifying the safety of the various abort situations. Since each engine performs differently, aborts are a function of which engine goes out. If there is a change in constraints, new requirements, or landing sites for flying abort situations, guidance modes and control gains may need changing. A lot of pre-mission trajectory analysis is needed for guidance targeting and planning. For a lighter versus heavier entering Shuttle Orbiter, a switch is used between different flight control sets, but these do not need to be redesigned[6]. Computer programs running on the ground determine the engine-out abort possibilities at any time during a Shuttle ascent. The astronauts can choose an abort mode corresponding to the one that the ground analysis determines is necessary for a given situation.

Recently-designed experimental vehicles have, in some areas, pushed to more autonomy and adaptability for the vehicle. The X-33, for example, was to have the on-board capability to evaluate the current performance and to re-target an alternate landing site if necessary[7]. The on-board computer would also re-design the trajectory if necessary to reach the nominal or alternate landing site. This technology, however, was developed specifically for the X-33 and is not a generic new capability for new launch vehicles, although it could be extended to be more general.

An effort was underway for a X-34 experiment to automatically target abort landings if all propulsion was lost. The system would determine which landing sites are reachable, designate the appropriate landing site, and fly there. It was for use in the low-Mach X-34 flights[8].

Goals for NASA's 2nd Generation RLV Program include significant improvements to vehicle reliability, safety, and cost. In particular, a goal is to reduce the probability of loss of crew to 1 in 10,000 missions (the Shuttle value is currently considered to be about 1 in 500). Another primary goal is to reduce the cost of flying a pound to orbit to no more than $1,000/lbm (compared to about $10,000/lbm on the Shuttle)[9].

This paper argues that advanced guidance and control (AG&C) technologies can contribute significantly to the 2nd Generation RLV goals. The evidence shows that AG&C technologies are required to achieve the desired improvements. The paper then specifies a breakout of the various aspects of AG&C technology that are necessary for working toward the goals. Finally, we describe current work that is underway to develop AG&C technology components, and where we believe additional work is necessary.

Safety, Reliability, and Cost Improvements from Advanced Guidance and Control

Advanced guidance and control technologies can offer the possibility of a safe return under a number of scenarios where it either would not otherwise be available or would require significant ground analysis to plan each scenario. Among these are:

•Crew module abort from any time during ascent
•Larger than expected vehicle dispersions, especially for first flight of a new vehicle (e.g. engine performance way off, such as with the Ariane 5 flight in July 2001)
•Vehicle mis-modeling that causes control problems--for example, poor aerodynamics (e.g. first Pegasus XL) or unexpected vibration mode problems (e.g. first Delta III)
•Engine failures--adapting autonomously vs pre-planning on the ground
•Aerosurface (hard over, frozen at some position, partially burned through, failed to null) or RCS failures
•Rotten vehicle performance due to some unknown cause(e.g. Japanese M-5 in Feb 2000)
•An unknown problem that affects performance (e.g. Taurus launch Sept 2001)
•Aborting due to other problems (e.g. something happens to life support, thermal protection, avionics cooling, or any other critical function during ascent requiring landing ASAP)

In fact, it is reasonable to have the goal of returning the vehicle safely in any situation where it can physically be returned safely. This means that the on-board capability would accommodate any situation where the vehicle is still controllable. Failure due to a problem that does not cause an immediate explosion is more likely to be the failure mode with a 2nd Generation RLV than with the Space Shuttle because the systems will be more robust and therefore more likely to shut down in a "benign" fashion if there is a problem.

There are many examples of expendable vehicles that have failed in the recent past where AG&C technologies would address the same failure mode had it occurred in a RLV. Figure 1 shows photos of some of these vehicles.

Table 1 lists failures since 1990, to U.S., European, Japanese, and Russian launchers (that are involved with U.S. companies), where AG&C technologies would address the failure mode had it occurred in a RLV. This represents 41% of all launch vehicle failures for these vehicles in this time period. The cross-cutting benefit of advanced G&C is fairly unique (Integrated Vehicle Health Management, IVHM, is related and is also cross-cutting) and is not available in most technology areas where the new technology applies to a particular component only (such as part of an engine, an actuator, a power supply, etc.). Note also that there are many additional failure modes that AG&C addresses in a RLV that are not part of an expendable vehicle (such as aerosurface failure modes).

Besides the safety improvements, AG&C technologies reduce cost. Classical AG&C techniques are used by NASA and industry, but carry a heavy operational cost. They require analysis when the payload or trajectory changes, require more analysis to analyze aborts and failures, and require significant time for each design cycle and each mission change. This is particularly important for 2nd Generation vehicles, where the number of failure scenarios covered is significantly enlarged. Use of classical techniques would be prohibitive in terms of the ground analysis effort, regardless of the fact that a ground effort would still cover only those failure modes that are anticipated prior to flight. Most total vehicle failures occur, of course, due to unanticipated problems.

Advanced technologies will automatically accommodate changes in vehicle models and failures without analysis to adapt to each case. They will significantly reduce the cycle time for guidance and control during vehicle design, since the algorithms will be much more adaptable to changes in vehicle models and missions without significant effort expended. Finally, they will significantly reduce the analysis required for new missions during vehicle operations, for the same reason. All these improvements contribute to reduced cost.

AG&C Technology Definitions

In order to cover autonomously for all the failure modes described above, we need a hierarchy of algorithms that must all work together:

- Autonomous flight manager (has also been referred to as a mission manager and an autocommander) that pulls data together regarding vehicle performance and flight dynamics, and decides how to react. Use of IVHM inputs along with system identification (described below) and on-board simulation of vehicle performance are probably all required. Some questions for this software include: Do we need to abort? Where should we try to land? What are the new trajectory constraints? Is any control reconfiguration necessary? Does the trajectory/guidance need to back off on commands to accommodate a control problem? A higher-level mission manager than this one might tell GN&C to abort when things are okay dynamically.
- On-board trajectory redesign with constraints. Note this is a very different question (in terms of vehicle dynamics and probably solution method) for powered ascent/abort versus

Table 1. Some Launch Failures (since 1990) that advanced guidance and control would address if the failure occurred in a RLV (U.S., European, and Japanese launchers, Zenit/Proton included due to Boeing/Lockheed Martin programs using those vehicles). Most of these failures can be found in Ref. 10. Some of the specific causes reside in a database compiled at NASA Marshall Space Flight Center.

Date	Launch Vehicle	Payload	Reason for Failure	RLV Action
7/17/91	Pegasus	Microsat 1	Pyrotechnic separation failure caused vehicle to steer off course at 1st stage sep., recovered but low orbit	Abort landing trajectory targeted
3/25/93	Atlas I	UHF F1	Inadequately torqued set screw caused reduced engine power	Abort deorbit and landing
5/27/93	Proton	Gorizont 39L	Multiple burn-throughs of combustion chambers, did not reach planned velocity	Abort landing trajectory targeted
1/24/94	Ariane 44LP	Turksat 1, Eutelsat 1	Premature shutdown of 3rd stage due to turbopump bearing overheating	Abort landing trajectory targeted
6/27/94	Pegasus XL	STEP-1	Poor aerodynamic data caused loss of control	Adapt to poor data to maintain control
8/5/95	Delta II	Mugunghwa 1	SRM failed to separate, causing lower than planned orbit	Abort landing trajectory targeted
5/20/97	Zenit 2	Kosmos-2344	2nd stage shutdown halfway through burn due to structural failure in engine	Abort landing trajectory targeted
2/21/98	H-II (Japan)	COMETS	Premature shutdown of 2nd stage due to faulty brazing in cooling system	Abort landing trajectory targeted
8/27/98	Delta III	Galaxy 10	Rolling mode not expected to be a problem; exhausted hydraulic fluid	Adapt to unexpected mode
9/9/98	Zenit 2	Globalstar FM5	Computer error caused very premature engine shutdown during 2nd stage	Abort landing trajectory targeted
10/20/98	Ariane 5	Amsat P3D	Roll torque from engine caused premature shutdown	Abort landing trajectory targeted or abort deorbit and landing
5/5/99	Delta III	Orion 3	Engine failure at ignition of upper stage due to poor brazing process in combustion chamber fabrication	Abort landing trajectory targeted
2/10/00	M-5 (Japan)	Astro-E (NASA-Japan)	1st stage corkscrewed through sky; 2nd stage okay	Abort landing trajectory targeted
3/12/00	Zenit 3SL	ICO F-1	2nd stage shutdown early due to software command mistake	Abort landing trajectory targeted
7/12/01	Ariane 5	BSAT2b, Artemis	Loss of thrust from 3rd stage (partial thrust) due to a combustion instability	Abort landing trajectory targeted
9/21/01	Taurus	Orbview, NASA QuikTOMS	Control problem at staging (seized actuator) hurt performance (not enough to reach orbit)	Abort landing trajectory targeted

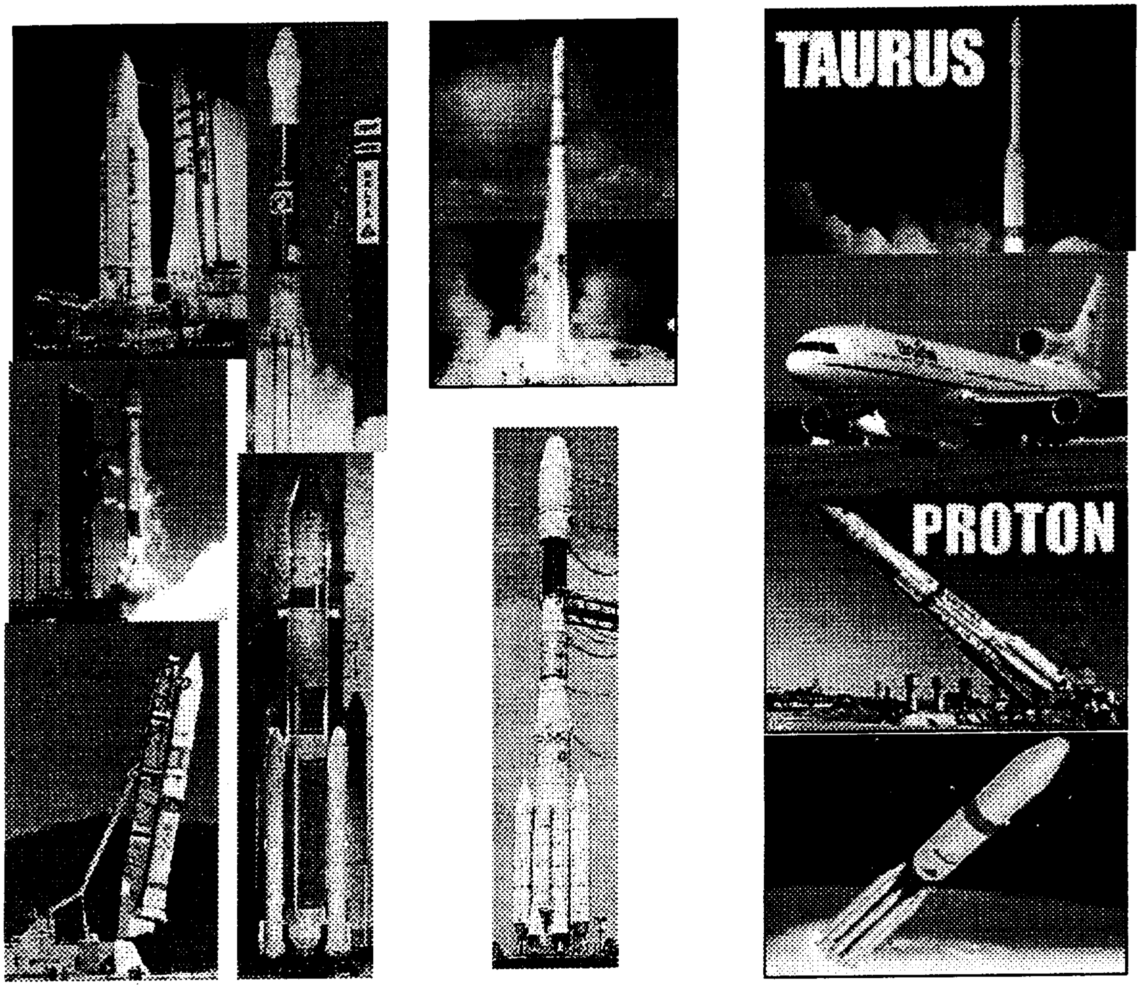

Figure 1. Launch Vehicles that failed during the past 10 years where AG&C technologies would address the failure mode had it occurred in a RLV. Clockwise from top right: Taurus, Pegasus, Proton, Delta 3, Ariane 4, H II, M-5, Atlas I, Ariane 5, Delta II, Zenit.

unpowered entry versus the final phases of flight.

- Guidance that adjusts the commands (which include commanded body attitude and possibly throttle setting) to fly the best way possible, accommodating control system limitations. A continuous trajectory redesign could function as a guidance method.
- Control (commands the torques about the various body axes in an effort to fly to the guidance commands) that reacts quickly to failures, and does not require ground-designed gain adjustment for different cases.
- Adaptive control allocation (allocates the torque commands to the various available control effectors, including thrust vector control, aerosurfaces, and reaction control system) to obtain the control needed from the available control effectors, in whatever state they are in.
- System identification to identify the effects of failures on the vehicle dynamics. System or parameter identification is using navigation data, effector commands, and any other available information to determine something about the plant (dynamic behavior of the vehicle). This may be determining the actual behavior of a specific surface, or may be determining the effect on the vehicle from the collective response to whatever is going on (such as a change in the capability to maneuver about a particular axis). The results of system identification must provide useful information to the vehicle guidance and control and must be available quickly to avoid loss of control.

Current Efforts in AG&C Technology as Applied to RLVs

A number of efforts are underway, in areas that apply to all the technologies required. Current adaptive efforts known to the author are described below. Currently proceeding company-internal efforts are not included.

Autonomous Flight Manager

Ohio University, under contract to the NASA 2nd Generation RLV Program, is developing an "autocommander" to serve this function. The autocommander is based on hybrid control methods[11]. This work is being applied to the ascent and entry phases of flight and is particularly focused on cascading between various options (starting at the inner-most G&C loop) depending on the current situation. NASA Johnson Space Center is developing a Shuttle Abort Flight Management (SAFM) tool for potentially providing on-board powered abort and entry landing site capability assessment[12] and plans to develop this capability further for the 2nd Generation RLV effort. The above two efforts are complementary in the sense that they focus on different aspects of managing the GN&C. As part of the RADX-34 experiment, Draper Laboratory developed the algorithms to autonomously choose abort landing sites for an unpowered entry vehicle (with no other failures except for a complete propulsion failure) at low Mach numbers[8]. This particular effort is currently stopped.

Ascent/abort trajectory design and guidance

Iowa State University, supporting Ohio University under the same contract as above, is designing an algorithm to design ascent and abort trajectories on-board, based on a finite difference method applied to the two-point boundary value problem[13]. An alternative approach is being developed at NASA Marshall Space Flight Center (MSFC). In this method, judicious approximations are made to reduce the order and complexity of the state/costate system, and multiple shooting is used[14]. Guided Systems Technologies Inc. is working another approach under a Phase 2 SBIR contract from Air Force Research Lab at Wright Patterson AFB, with partial funding from the NASA 2nd Generation RLV office. In this approach, an optimal vacuum solution is obtained first, and homotopy is used to introduce the atmospheric terms and constraints[15]. This last method contains some company proprietary code.

Entry trajectory design and guidance

As part of the Universal Space Lines contract funded by the 2nd Generation RLV Program, University of California at Irvine is pursuing development of an entry trajectory design and guidance procedure based on extension of the Shuttle trajectory design methods to three dimensions. The planning algorithm generates reference drag acceleration and lateral acceleration profiles, along with the reference state and bank angle profiles. A feedback linearization control is used to track the reference profiles[16]. This work has also been partially supported by a grant from NASA MSFC. Under the afore-mentioned Ohio University contract, Iowa State University is also developing an entry trajectory design and guidance method[17]. This work has also been partially supported by a grant from NASA MSFC. The trajectory design method uses quasi-equilibrium glide, combined with a predictor-corrector method, to choose parameters for entry. The guidance tracks all trajectory states. NASA MSFC has developed a linear quadratic regulator entry guidance method that performed well in early tests[18]. NASA MSFC has also developed a predictor-corrector trajectory design combined with the LQR guidance as a further approach[19].

Terminal Area Energy Management (TAEM) and Approach/Landing (A/L) trajectory design and guidance

Barron Associates Inc. has a Phase 2 SBIR with the Air Force Research Lab at Wright Patterson AFB, with partial funding from the NASA 2nd Generation RLV office, for continuing development of their approach to trajectory redesign for the TAEM and A/L phases[20]. This method is focused on accommodating aerosurface failures and gross mis-modeling of the vehicle during the final phases of flight. The AFRL SBIR effort is focused on flight tests (on the F-16 Vista aircraft and/or the X-40A approach and landing testbed) of specific failure scenarios. The flight test effort is currently funded separately and is proceeding toward flight in 2004. Barron Associates also has a Phase 2 SBIR with NASA to apply this technology to all identified failure modes during the TAEM and A/L phases. The method involves a guidance gain reconfiguration algorithm, along with trajectory reshaping using an on-board system to choose the best trajectories from ones designed on the ground. In addition, Draper Laboratory has conducted independent research and development on the on-board design of A/L trajectories to maximize energy margins[21]. This effort did not consider aerosurface failures. The University of Missouri has recently explored some concepts for using neural nets to design these trajectories on-board[22]. The trajectories are generated using adaptive critic-based neural networks. This method, and approaches based on fuzzy logic and on parameter optimization, are proceeding with low levels of support through NASA's Faculty Fellowship Program and through NASA's Graduate Student Researchers Program. Researchers at the Air Force Research Lab are studying on-board determination of reachable landing sites with control surface failure[23]. Experimental vehicles currently in work (X-37 and X-38) use Shuttle guidance, which includes trajectory adjustment to account for energy dispersions, but not trajectory redesign that includes more drastic problems.

Control System
Ohio University is working in this area also. Combined with the University of Alabama in Huntsville, they are investigating a combination of sliding mode control[24] and control by trajectory linearization[25]. Both of these methods showed promise in early testing. This work is also partially supported by a grant from NASA MSFC. Georgia Institute of Technology is pursuing a method based on neural network on-board learning, combined with pseudo-control hedging[26]. This work is supported by a grant from NASA MSFC. The University of Missouri has a grant from NASA MSFC to work on control using neural networks, but this development is not as far along yet. In addition to the methods mentioned above, recent work has included a hybrid direct-indirect adaptive control system[27] and a linear parametrically varying method[28]. These methods are not currently being pursued. Naval Air Systems Command has done a lot of comparison work[29-31]. Some of the above control designs were originally worked as part of the Air Force RESTORE Program that flew adaptive control on the X-36 aircraft[24,26]. The X-38 experimental vehicle uses dynamic inversion control, but adaptive elements are not incorporated yet. NASA JSC has plans to lead work in this area. The X-37 experimental vehicle uses PID control for longitudinal motion and gain-scheduled linear quadratic regulator control for lateral motion. None of the methods currently being pursued have been worked for all phases of flight.

Control Allocation
Again under the Ohio University contract, Auburn University has been working on a method for adaptive control allocation[32]. This method responds to reported and/or sensed changes in vehicle health (actuator failures/degradation) in order to maintain control allocation performance, by using quadratic programming to dynamically match the commanded torque with minimum actuator deflection. The same research group is working on on-line computation of the local attainable moment set, for use in control allocation and also for passing these data to the control system and to the autonomous flight manager[33]. We are not aware of other work in adaptive control allocation as applied to reusable launch vehicles.

System Identification
Work at Barron Associates[20] includes a modified sequential least squares approach to this problem, which has successfully been demonstrated for some applications. It has not been shown to work for most RLV phases of flight. Air Force Research Lab[27] has also pursued on-line system identification through exciting the surfaces using null-space injection. An effort to apply neural nets to RLV System ID has begun under NASA's Faculty Fellowship Program.

Integration and Testing
The AG&C Project, sponsored by the X-33 Program Office, examined a number of guidance and control methods for their benefits to 2nd Generation RLV Program goals. It used a high-fidelity vehicle simulation to test for the ability of the algorithms to successfully accommodate various failures, dispersions, and mis-modeling[34]. The Ohio University contract, besides involving the development of algorithms, includes integrating them into an architecture and testing it to a high level of fidelity in a real-time simulation.

What Else Needs to be Done?

Prior to having the right technology, we need to know what the requirements for the technology are. By specifying the job to be done, we will be able to plan tests that verify that the methods chosen satisfy the overall 2nd Gen need. The detailed requirements and associated tests have not been developed yet, although top-level requirements have recently been drafted. Generation of 2nd Gen GN&C requirements and flow down into testing is the first job still to be done. Potential builders of the RLV vehicle must be a part of this process, to ensure their needs will be met.

The biggest job left in meeting the goals for these technologies and in showing that they are ready for flight is in the integration and testing area. However, some algorithm work is also necessary, as described next. Note that methods which may satisfy the necessary requirements but can't be ready within the time frame needed (fully ground-tested by 2006, enough that a flight vehicle development can confidently choose this technology) will not be considered. Also, we are not suggesting examination of every possible method. If a chosen technology satisfies the requirements, including fitting in the expected on-board computing capability, then we are done. We also describe the integration and testing work that is necessary below.

Autonomous Flight Manager
There is only one approach being developed fully (Ohio University). Because this method has not been tested and must meet a challenging goal, the risk is high and another approach is needed. Pursuing an on-board implementation of the Shuttle SAFM algorithms would be one option for a second approach. Efforts using this second approach have begun. These two approaches do not entirely overlap, so that the best solution may be a combination of the two.

Ascent/abort trajectory design and guidance
The current efforts, involving three independent approaches that are oriented toward solving this problem, are sufficient.

Entry trajectory design and guidance
There are currently three independent approaches being researched to solve this problem (three trajectory design approaches and three guidance approaches). This should be sufficient.

Terminal Area Energy Management (TAEM) and Approach/Landing (A/L) trajectory design and guidance
There is only one approach being fully pursued that addresses the total scope of the problem (including recovering from failures by changing the trajectory). It is not clear yet whether this approach will successfully address both the safety and cost goals of the program, so more is needed. Some methods that may pay off in this area are using multiple shooting to pick the right parameters in a trajectory design scheme, using neural networks for trajectory redesign, and using fuzzy logic. The trajectory can be broken up into a fairly small number of parameters that need to be chosen, so these approaches have some promise. The initial efforts in these areas should be continued to determine which methods offer the best advantage.

Control System
Although a significant effort is being pursued with the Ohio University contract, there should be at least one alternative. The neural network approach developed by Georgia Tech showed promise in early testing and should be continued as an alternative. These two methods are being worked for the ascent and entry phases, and should be extended through the final phases of flight. There are other promising approaches. A fuzzy logic method might be advantageous in some respects. Dynamic inversion with adaptation may be a good approach. Expertise developed at Naval Air Systems Command applies in a significant way to choosing the best algorithms for further pursuit.

Control Allocation
There is only one approach being pursued at the current time. We believe there should be at least one additional approach pursued, since this algorithm must successfully adapt to a range of failure and mis-modeling cases. Options include fuzzy logic and neural net-based approaches. Some time should be spent identifying the most promising options.

System Identification
There is currently no focus on system identification. The Barron method should be examined in high-fidelity simulation to demonstrate its effectiveness for all phases of flight. It would be beneficial to also pursue another method, maybe a neural network approach, by extending the initial work that has started. Again, some time should be spent examining the options and identifying the most promising approaches.

Integration and Testing
Much is lacking in the integration of the various algorithms in order to demonstrate that they satisfy the requirements. We know the safety and cost goals. These translate into a requirement for the guidance and control to be able to successfully land the vehicle in any situation where it is possible to successfully return to fly another day. We need to identify how it can be verified that this requirement is met. The requirements for the various test cases to demonstrate success in meeting these needs across the board must be developed. Use of the existing test cases[34] plus Shuttle astronaut simulation historical scenarios will furnish a big part of the needed test scenarios. NASA JSC is beginning work to identify these.

The only currently existing, verified RLV models that are high fidelity are Space Shuttle models. Verified simulations currently exist with Shuttle models, and we know how the Shuttle flies in reality. This is probably the best set of models to use for the next set of tests on the various potential methods. Ultimately, the methods must be shown to also work for the various 2nd Generation RLV concepts. As the concepts mature during the next several years, the algorithms must be applied to these vehicle concepts to show requirements are met in simulation.

All the various methods under development need to be integrated into a guidance and control architecture, which must be tested in a high-fidelity simulation (Shuttle simulation at first). We want to find the architecture that best supports the requirements (this means necking down among the algorithm choices, finally to one method for each part of the architecture) and then test it at higher fidelity levels, ultimately showing it will fit on the expected flight computers and run in real time. A complete set of simulations must show the architecture meets all requirements. Some alternative algorithms may need to be retained long enough to show the chosen methods meet all requirements. Real-time verification simulations will demonstrate readiness for flight. Flight tests, if conducted, would provide confidence to potential RLV builders that these new methods will safely fly their vehicles.

Summary

Advanced Guidance and Control technologies offer the chance to significantly improve the safety of the next generation of reusable launch vehicles, and to reduce expenses involved with guidance and control analysis and mission planning. Significant work is ongoing, but more effort is required to meet the safety goals and to bring the technology up to a sufficient readiness level for committing to the new RLV. We have reviewed the current efforts and defined a vision for what else is necessary.

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