

Methodology for Prototyping Increased Levels of Automation for Spacecraft Rendezvous Functions

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The Crew Exploration Vehicle necessitates higher levels of automation than previous NASA vehicles, due to program requirements for automation, including Automated Rendezvous and Docking. Studies of spacecraft development often point to the locus of decision-making authority between humans and computers (i.e. automation) as a prime driver for cost, safety, and mission success. Therefore, a critical component in the Crew Exploration Vehicle development is the determination of the correct level of automation. To identify the appropriate levels of automation and autonomy to design into a human space flight vehicle, NASA has created the Function-specific Level of Autonomy and Automation Tool. This paper develops a methodology for prototyping increased levels of automation for spacecraft rendezvous functions. This methodology is used to evaluate the accuracy of the Function-specific Level of Autonomy and Automation Tool specified levels of automation, via prototyping. Spacecraft rendezvous planning tasks are selected and then prototyped in Matlab using Fuzzy Logic techniques and existing Space Shuttle rendezvous trajectory algorithms.

I. Introduction

The National Aeronautics and Space Administration (NASA) recently established a new vision for space exploration that calls for the design of the next generation of spacecraft to explore the solar system.¹ The new spacecraft, called the Crew Exploration Vehicle (CEV), will be capable of rendezvousing with the International Space Station (ISS), returning to the moon, and eventually enabling human exploration of Mars. These missions present unique challenges such as increased communication delays and spacecraft rendezvous in lunar and Martian orbits. To meet these challenges there must be an increased level of vehicle autonomy^a over previous human spacecraft.² Because of limited crew sizes many of the increases in autonomy will be realized by the use of on-board automation^b. As a result, the CEV necessitates higher levels of automation than previous NASA vehicles. A key technology to the success of the CEV is developing Automated Rendezvous and Docking (AR&D).³

The precise breakdown of responsibility between the crew and on-board computers, or level of automation, has not been formally established for the CEV. One critical area is in the division of authority for decision-making tasks. Studies of spacecraft development often point to the locus of decision-making authority between humans and computers (i.e. automation) as a prime driver for cost, safety, and mission success.⁴

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^aAutonomy is defined as the ability for a vehicle and its on-board systems to perform a function without external support. On-board systems include humans that are on-board. The level of autonomy is the degree to which the function can be performed by on-board systems without ground systems support.

^bAutomation is defined as the ability for computer systems to perform a function without human support. The level of automation is the degree to which the function can be performed by computer systems without human support.

Therefore, a critical component in the CEV development is the determination of the appropriate level of automation.

A. Automation in Human Spaceflight

Historically, NASA has operated at low levels of automation and relied heavily on manual control and ground based planning. In early spacecraft such as Mercury, Gemini, and Apollo, computer technology limited the amount of automation. However, some routine and repetitive tasks were performed automatically. In some cases the automated functions were inhibited by the ground or crew due to a lack of trust in the automation.

The Space Shuttle has a variety of automated functions for both ground and on-board systems. There are automated responses for many single systems-failure cases, requiring limited human interaction, but multiple failure cases are not automated. During the design of the Shuttle there were plans for on-board automation of numerous functions, but many of these plans were eliminated because of cost and schedule pressures. Since the first launch of the Shuttle, many functions have been automated with mixed results. Overall, the Shuttle relies heavily on humans for execution of virtually all of its on-board and ground-controlled functionality.

The ISS was intended to have increased levels of automation for many major functions in order to meet the needs of continuous operations. Many of the space station's subsystems include automated functionality to maintain and conduct nominal operations. However, much of the automated functionality is difficult and costly to modify. The result is that many functions are disabled or bypassed via operational workarounds. There have been some recent improvements to ISS automated operations such as the inclusion of the Time-liner software used for command and control functions.¹

For the CEV, new approaches must be used to determine the correct levels of automation. One particular area is the automation of rendezvous and docking functions.

B. Automated Rendezvous and Docking

Rendezvous of spacecraft in orbit has been a critical task throughout the history of spaceflight. It was identified as a necessary activity early on in the development of the United States space program and was the primary technical objective of the Gemini missions.⁵ In the Apollo program, the Lunar Module (LM) had to successfully rendezvous with the Command and Service Module (CSM) on its return from the lunar surface. Rendezvous also allows for on-orbit assembly, which provides flexibility in mission design by eliminating the requirement for one large booster rocket to carry every spacecraft component in a single launch.

Early Space Shuttle design studies included high levels of autonomy and automation for rendezvous capabilities due to rendezvous experience gained during Apollo and significant advancements in on-board computer capabilities. As late as 1976 there existed requirements for nominal rendezvous planning to occur using on-board computers with little or no support from Mission Control.⁵ However, budget and schedule issues limited the on-board computer capability, which made these requirements difficult to meet. It was decided to reduce on-board targeting to include only burns supported by on-board relative navigation sensors. The automation of Shuttle rendezvous tasks was further complicated by a wide variety of missions. Early rendezvous missions were deploy/retrieval of satellites, missions with multiple rendezvous, and retrieval or servicing of un-cooperative target satellites.

As the role of the Shuttle changed to primarily rendezvous with the ISS, procedures became more standardized. This allowed for automated planning capability of proximity operations (prox ops) to be developed such as the Rendezvous and Prox Ops Program (RPOP) tool. The RPOP tool is hosted on a laptop computer and used to provide the crew a relative motion display and piloting cues. There have also been increases in the automation of ground-based tools used in the Mission Control Center (MCC). However, much of the planning and execution of Shuttle rendezvous and prox ops remain at low levels of automation.⁶ The lowest levels of automation are for decision-making functions, which can be the most challenging to automate.

All of the CEV missions will require successful rendezvous, and the CEV requirements call for automated rendezvous and docking.⁷ The requirements include uncrewed docking to the ISS, safe return without communication with the ground, and operation of the CEV with only a single crew member. These requirements result in a significant amount of on-board automation for rendezvous and docking functions. Since the existing levels of automation for these functions is low, this is a risk area for CEV development. In particular, the automation of decision-making functions will be critical to the success of automated rendezvous and docking for the CEV.

C. Function-specific Level of Automation and Autonomy Tool

By finding the correct levels of automation, NASA can vastly improve the probability of mission success, increase safety, and decrease overall cost. To identify the appropriate levels of automation and autonomy to design into a human space flight vehicle, NASA has created a method called the Function-specific Level of Autonomy and Automation Tool (FLOAAT).^{4,8}

The backbone of FLOAAT is a practical construct of separate levels of automation and autonomy for each of the 4 stages of decision-making (Observe, Orient, Decide, and Act),⁹ which leverages off theoretical constructs.^{4,8} These Levels of Autonomy and Automation (LOAAs) are divided into a 5-point scale for autonomy as shown in Figure 1, with level 1 corresponding to complete ground authority and level 5 corresponding to complete on-board authority, and an 8-point scale for automation as shown in Figure 2, with level 1 corresponding to complete human authority and level 8 corresponding to complete computer authority. The FLOAAT process employs a survey in which domain-area experts evaluate a variety of issues that would each lead to more or less autonomy or automation for a particular function (or task). These results are then mapped onto the corresponding LOAA scales. The output of FLOAAT is a level of automation and autonomy for each function (or task) evaluated in the process.

Level	Observe	Orient	Decide	Act
5	The data is monitored onboard without assistance on the ground.	The calculations are performed onboard without assistance on the ground.	The decision is made onboard without assistance on the ground.	The task is executed onboard without assistance on the ground.
4	The data is monitored onboard with available assistance on the ground.	The calculations are performed onboard with available assistance on the ground.	The decision is made onboard with available assistance on the ground.	The task is executed onboard with available assistance on the ground.
3	Both the ground and the onboard have the capability to monitor the data.	Both the ground and the onboard have the capability to perform calculations.	Both the ground and the onboard have the capability to make the decision.	Both the ground and the onboard have the capability to execute the decision.
2	The data is monitored on the ground with available assistance onboard.	The calculations are performed on the ground with available assistance onboard.	The decision is made on the ground with available assistance onboard.	The task is executed on the ground with available assistance onboard.
1	The data is monitored on the ground without assistance onboard.	The calculations are performed on the ground without assistance onboard.	The decision is made on the ground without assistance onboard.	The task is executed on the ground without assistance onboard.

* "Without assistance" does not preclude data access

Figure 1. FLOAAT Level of Autonomy Scales, v4.0

D. Research Objectives and Approach

This research seeks to prototype a sub-set of the rendezvous and/or prox ops functions at the levels of automation specified using FLOAAT. By prototyping at these levels, the accuracy of the FLOAAT outputs can be evaluated. Modern decision-making algorithms will be used to help improve the efficiency, safety, and quality in the execution of selected rendezvous and prox ops planning tasks. This research only addresses the division of human versus computer responsibility (automation) and will not address the issue of ground versus on-board responsibility (autonomy). The issue of autonomy, although important, is difficult to prototype until a more detailed design of the ground-control architecture and on-board computing and display capabilities is available.

The research objectives are to:

1. Prototype selected rendezvous and/or prox ops functions at the levels of automation determined by the Function-specific Level of Autonomy and Automation Tool (FLOAAT) process.
2. Evaluate the prototype versions by comparing to Shuttle/ISS implementations of the same functions.
3. Use this comparison to evaluate the accuracy of the FLOAAT recommended level of automation (LOA).
4. Evaluate the selected decision-making algorithms as applied to the selected functions

A final evaluation will be made to determine if the level of automation was appropriate for each prototyped function and provide suggestions for improvement. This includes an evaluation of the prototyping process, decision-making techniques used, and the effectiveness of operating at the levels of automation specified by the FLOAAT process. The results of the prototyping effort will be used to gauge the accuracy of the

Level	Observe	Orient	Decide	Act
8	The computer is responsible for gathering and filtering data without displaying any information to the human.	The computer overlays predictions with analysis and interprets data for a result that is not displayed to the human.	The computer performs the final ranking task, and does not display the result to the human.	The computer executes the decision and does not allow any human interaction.
7	The computer is responsible for gathering and filtering data without displaying any information to the human. Though, a "program status indicator" is displayed.	The computer overlays predictions with analysis and interprets data for a result which is only displayed to the human if result fits programmed context (context dependant summaries).	The computer performs the final ranking task and displays a reduced set of ranked options without displaying "why" the decision was made to the human.	The computer executes the decision and only informs the human if required by context. The human is given override ability after execution when physically possible.
6	The computer is responsible for gathering, filtering, and prioritizing information displayed to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results for potential override.	The computer performs the ranking task and displays a reduced set of ranked options while displaying "why" the decision was made to the human.	The computer executes the decision, informs the human, and allows for override ability after execution when physically possible. In the event of a contingency, the human can independently execute the decision.
5	The computer is responsible for gathering and displaying unprioritized information for the human. The computer filters out the unhighlighted data for the human to monitor.	The computer overlays predictions with analysis and interprets data. The human is the backup for interpreting data.	The computer performs the ranking task. All results, including "why" the decision was made, are displayed to the human.	The computer allows the human a context-dependant time-to-veto before executing the decision. In the event of a contingency, the human can independently execute the decision.
4	The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The computer highlights the relevant non-prioritized information for the human to monitor.	The computer is the prime source for analyzing data and making predictions as a trusted calculator. The human is the prime source for interpreting data.	Both the human and the computer perform the ranking task, the results from the computer are considered prime.	The computer allows the human a pre-programmed time-to-veto before executing the decision. In the event of a contingency, the human can independently execute the decision.
3	The computer is responsible for gathering and displaying unfiltered, unhighlighted, and unprioritized information for the human. The human is the prime monitor for all information with computer backup.	The computer is the prime source for analyzing data and making predictions with human checks of the calculations. The human is the only source for interpreting data.	Both the human and the computer perform the ranking task, the results from the human are considered prime.	The computer executes the decision after human grants authority-to-proceed. In the event of a contingency, the human can independently execute the decision.
2	The human is the prime source for gathering and monitoring data, with computer backup.	The human is the prime source for analyzing data and making predictions, with computer verification when needed. The human is the only source for interpreting data.	The human is the only source for performing the ranking task, but the computer can be used as a tool for assistance.	The human is the prime source for executing the decision, with computer backup for contingencies (e.g. deconditioned humans).
1	The human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) data.	The human is the only source for analyzing data, making predictions, and interpreting data.	The human is the only source for performing the ranking task.	The human is the only source for executing the decision.

*Humans still have access to data at the highest Levels of Automation, but it is not displayed by default

Figure 2. FLOAAT Level of Automation Scales, v4.0

FLOAAT tool to select appropriate levels of automation. It will also determine the applicability of the selected decision-making algorithms for use in human spaceflight.

The methodology to prototype spacecraft rendezvous functions at increased levels of automation is described in this section. The first step is to select appropriate rendezvous functions to prototype at the FLOAAT specified LOAs. The objectives and constraints of candidate functions are captured in the flight rules and procedures used for Shuttle/ISS rendezvous and docking. Once a set of rendezvous functions is selected, a survey of available Artificial Intelligence (AI) decision-making techniques is conducted to determine which technique is the most suitable for prototyping the selected rendezvous functions. Then, a prototype is created to implement the selected rendezvous functions at the appropriate LOAs as specified by the FLOAAT process. The effectiveness of the prototype for nominal and off-nominal test cases is compared to current methods used in Shuttle/ISS rendezvous. This evaluation includes an assessment of the selected AI technique and the FLOAAT selected LOAs. The results and conclusions of this research are presented including recommendations for future work.

II. Technical Background

A. Introduction

During a given NASA mission, numerous decisions are made that affect the success of the mission and the safety of the crew. To date, the vast majority of this decision-making is completed on the ground by flight controllers using operational guidelines and constraints captured in ‘flight rules’. Future NASA missions to the moon and Mars will require increased use of on-board computer-based decision-making because of communication delays with the ground and limited crew sizes.² Recent advancements in computing speed and the development of reliable computer-based decision-making methods can be used to meet this requirement. NASA developed the FLOAAT process to determine the correct levels of automation and autonomy for human spacecraft functions. This process was used to determine the appropriate levels of automation and autonomy for CEV rendezvous and prox ops in an early development effort.¹⁰

B. Space Shuttle Orbiter and International Space Station (ISS) Rendezvous Profile

This section discusses the Space Shuttle rendezvous profile for background necessary to understand Shuttle rendezvous flight rules. The baseline Shuttle rendezvous profile is known as ‘stable orbit rendezvous’. This trajectory profile has been used in the Shuttle program since 1983 for rendezvous with satellites, the Mir Space Station, and the ISS.⁵ Figure 3 shows the relative motion of the Space Shuttle Orbiter with respect to the target spacecraft in a Local Vertical Local Horizontal (LVLH) reference frame. The origin of the LVLH frame is the target vehicle with the V-bar indicating the direction of the target spacecraft orbit and the R-bar directed toward the center of the body being orbited (i.e. Earth), this is shown in Figure 4. Several orbital burns are conducted by the Orbiter during the rendezvous profile to change the relative motion of the two spacecraft. The burns are computed as velocity changes (ΔV 's) that the Orbiter executes using Orbiter Maneuvering System (OMS) thrusters and/or Reaction Control System (RCS) thrusters. The burns are executed in order from right to left and indicated by black squares with labels denoting the type of burn executed. The burn sequence and associated Shuttle nomenclature is as follows:⁶

- Nth Central phasing burn (NC). The NC burn allows the Orbiter to catch up with the target at the proper rate.
- Nth Corrective Combination burn (NCC). NCC targets the desired downtrack, out of plane position, and height at a future point (e.g. Ti).
- Transition initiation burn (Ti). This burn targets the Orbiter for a near-intercept trajectory with respect to the target spacecraft.
- Midcourse Correction (MC1 - MC4). The MC burns are small correction burns executed between Ti and the manual prox ops phase.

This research focuses on the near-field rendezvous phase of the Rendezvous, Proximity Operations, and Docking (RPOD) operations. The rendezvous phase occurs after insertion into orbit following launch and concludes at the prox ops phase. Figure 3 shows the burns that comprise the near-field portion of the

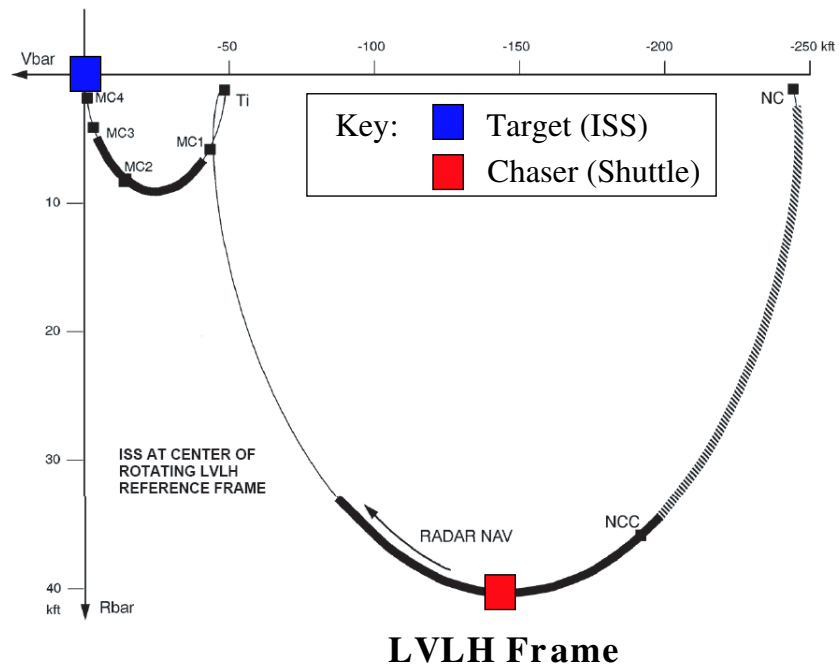


Figure 3. Stable orbit rendezvous

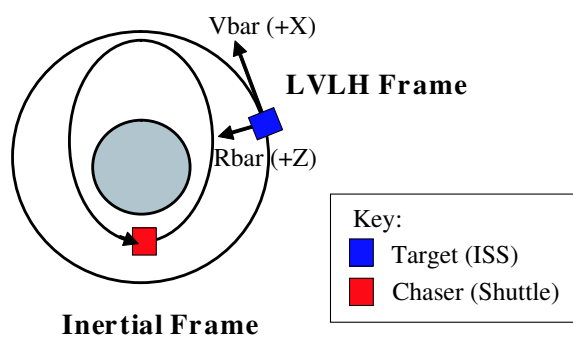


Figure 4. Inertial and LVLH Reference Frames

rendezvous profile, which occurs in the hours just prior to docking. A large portion of the RPOD decision-making occurs during the near-field rendezvous portion of the flight. This figure does not show the prox ops phase of docking. The prox ops phase occurs when the chaser vehicle (Shuttle or CEV) is in close proximity with the target vehicle (ISS). This phase begins when the range is less than 1000 ft and LVLH relative velocity is less than 1 ft/sec in each axis.

During prox ops, different techniques are used to control the orbiter trajectory than those used during rendezvous operations.¹⁰ These techniques rely on crew visual observations and piloting techniques to achieve a desired relative state. Therefore, Prox Ops operations are primarily a guidance task which does not include the type of decision-making this research seeks to automate. The focus of this research will be the decision-making functions performed during near-field rendezvous.

C. Rendezvous, Proximity Operations, and Docking (RPOD) FLOAAT Study

In 2005, during early CEV requirements development, NASA Johnson Space Center coordinated a study to evaluate the FLOAAT process.¹⁰ The study goal was to use FLOAAT to develop Level 2 requirements for Rendezvous, Proximity Operations, and Docking (RPOD) functions. Upon completion of the study, 21 function-specific RPOD requirements were developed with clear decision-making authority specified. Potential improvements to the FLOAAT Process were identified and completed. As a result, the FLOAAT process was recommended as the methodology for development and analysis of Autonomy and Automation requirements for the CEV.

1. Reference Levels of Autonomy and Automation

One of the key outputs of this study are the current levels of automation and autonomy for Shuttle and ISS rendezvous missions. The required levels of automation and autonomy based on preliminary CEV requirements are also captured in this study. Collectively, these are referred to as the ‘reference levels of automation and autonomy’. These levels are helpful in evaluating how the FLOAAT outputs compare to the current Shuttle/ISS implementation and the CEV requirements. For the example in Figure 5, the text of the RPOD requirement is shown in yellow, the current Shuttle/ISS autonomy and automation values and associated reference text are shown in green, and the CEV-directed levels are shown in blue.⁴

From: FLOAAT RPOD Functional Requirements Document Baseline Version				
Task	Requirement	Rationale	Potential Implementation	OODA Type
5.3.2 Rendezvous Trajectory Maintenance	[FLOAAT_CEV_0190] The CEV Systems shall decide whether to continue on the current trajectory plan or to modify the current trajectory plan during the Rendezvous Flight Phase.	Rationale: After determining an alternate plan, the system must determine whether it is appropriate to switch to this plan. This requirement allows for the possibility that humans would be involved in determining whether to switch from the previous plan to an alternative plan.	Potential Implementation: If the current plan does not meet rendezvous objectives and constraints, and an alternate plan does meet them, switch to the alternate plan.	OODA Type: Decide
	Current Shuttle/ISS RPOD Reference			
	Automation Level	Automation Reference	Autonomy Level	Autonomy Reference
	2	The FDO and the Prop officer are responsible for deciding if a change to the current plan is necessary. This may include using a computer as a tool, but not as a partner in the decision process.	1	This is only performed on the ground during the Rendezvous Flight Phase.
CEV/EDS RPOD as Described in the Level 1 Documents Reference				
Automation Level	Automation Reference	Autonomy Level	Autonomy Reference	
6	The human should be shown why the highest ranked option was chosen. CTS0300H The CTS shall provide autonomous operations linked to the mission phase and function with an objective of autonomous operations throughout the mission. Rationale : A	3	CTS0300H The CTS shall provide autonomous operations linked to the mission phase and function with an objective of autonomous operations throughout the mission.	

Figure 5. Reference Levels of Automation and Autonomy

The results of the FLOAAT RPOD study are a valuable tool for determining the correct level of automation for CEV rendezvous functions. This research uses the results of the FLOAAT RPOD study to

determine a set of functions to prototype. The prototype will be used to verify the accuracy of the FLOAAT output and determine AI decision-making techniques for use in automation of CEV rendezvous functions.

III. Rendezvous Function Selected for Prototyping

Candidate high-level functions resulting from the FLOAAT RPOD study are evaluated based on the description of the function, current Shuttle/ISS levels of automation, and FLOAAT recommended levels of automation. By examining the rendezvous flight rules,¹¹ additional details captured in the FDO On-Orbit Handbook⁶ and discussions with NASA rendezvous experts, the high-level functions are then decomposed into more specific candidate functions suitable for prototyping. From this process the Time-of-Ignition (TIG) slip planning is selected for prototyping as a decomposed requirement of [FLOAAT_CEV_0270].

[FLOAAT_CEV_0270] If an abort is necessary during the Rendezvous Flight Phase, the CEV Systems shall decide which abort plan is necessary.
OODA Type: Decide

- Current Shuttle Level of Automation: 2
 - The human performs all ranking tasks, but the computer can be used as a tool for assistance
- FLOAAT recommended Level of Automation: 4
 - Both the human and the computer perform ranking tasks, the results from the computer are considered prime.
 - Potential Implementation: Automated flight-rule-based process that determines which abort mode is best, with crew back-up and override.

Note: In this context “abort” is considered to mean slipping the TIG time

Figure 6. Candidate High-Level Rendezvous Function

A. Time of Ignition (TIG) Slip Planning

For requirement [FLOAAT_CEV_0270] (‘...decide which abort plan is necessary’), the function selected for prototyping is to determine the duration a burn can be slipped (delayed) before the burn can no longer be executed. In this context ‘abort’ is considered to mean executing a burn after the planned Time of Ignition (TIG). This is known as a ‘TIG slip’, and the maximum TIG-slip duration is calculated for every burn in the rendezvous plan. A TIG slip could be necessary if a burn needs to be delayed for any of several reasons including chaser vehicle system issues, target-vehicle system issues, etc.. Since the burn now occurs at a different time and location in the trajectory, slipping a planned burn will result in different relative motion than originally planned. It also results in increased propellant usage to return to the planned trajectory. Typically, the duration of a TIG-slip is limited by deviations in the resulting relative motion or increased propellant usage. For most burns, the TIG-slip duration is less than 5 minutes.

In the current implementation of this function, a computer program is used as a tool, and a human flight controller iteratively runs the program to determine the maximum slip duration for each burn⁶ (level of automation of 2 on the ‘decide’ scale). The FLOAAT recommended level of automation for [FLOAAT_CEV_0270] is 4, ‘Both the human and the computer perform ranking tasks, the results from the computer are considered prime’. Therefore, the prototype should result in an automated process that determines maximum TIG-slip duration with this result considered primary while still allowing crew/flight controller back-up and override capability. The prototype automates the determination of maximum TIG-slip for the NC (phase change) burn shown in Figure 3. There are two ways to execute a TIG slip. These two methods are called an ‘inertial TIG slip’ and an ‘LVLH TIG slip’.

In an inertial TIG slip, the burn targets (target ΔV ’s computed in the inertial frame) for the original burn are used with the Orbiter in an inertial attitude hold. The resulting burn will be slightly different than originally planned when the TIG is delayed. This is because the LVLH and inertial frame are slowly drifting out of alignment. The frames are only equivalent for the planned TIG time, not for the new TIG time. The LVLH frame rotates at the orbit rotation rate of the ISS, which is equal to 4 degrees per minute. Therefore,

the longer the TIG slip is the bigger the difference will be between the planned and actual trajectories. As the difference in trajectories increases, the cost in terms of propellant also increases.⁶

Figure 7 plots a family of relative motion trajectories used for TIG-slip planning of the NC burn for an inertial TIG slip. This is an example of the TIG-slip analysis that flight controllers perform for each rendezvous burn during every Shuttle mission. The hand written markings denote the nominal trajectory (labeled 'NOM'), 1-minute (labeled '1'), 2-minute (labeled '2'), and 3-minute (labeled '3') inertial TIG slips. In each case, the NC burn must be successfully executed to reach the desired relative position at the correct time to execute the T_i burn. Also included are the propellant costs for each of the slips written in terms of ΔV in feet per second (ft/sec). For each TIG-slip duration, the flight controller uses the relative motion plot to determine if the trajectory violates a 4 nautical mile (nm) constraint on relative distance between the Orbiter and ISS (located at the origin). In the example given in Figure 7, this constraint is shown as a solid gray line. For this case, it indicates that the 2-minute TIG slip will just barely violate the relative motion constraint. In terms of relative motion, the maximum TIG slip would be slightly less than 2 minutes. For this case, the inertial TIG slip of slightly less than 2-minutes will cost approximately an additional 13 feet per second of ΔV over the nominal burn plan. After evaluating the maximum TIG slip based on relative motion, the maximum slip duration and ΔV cost is captured to use for comparison to the LVLH TIG-slip method.

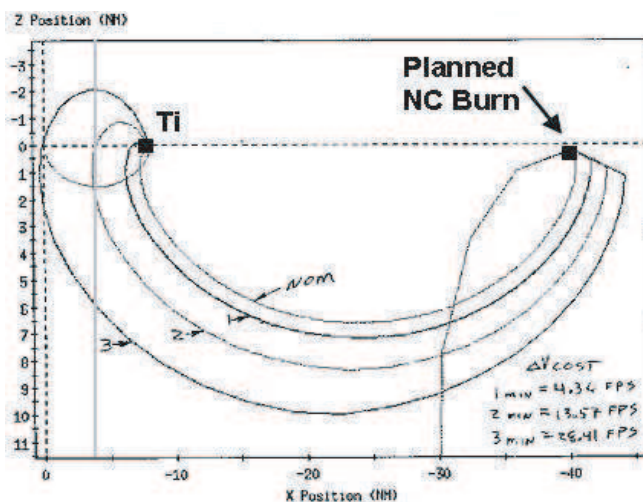


Figure 7. Inertial TIG slip

For an LVLH TIG slip the burn targets stay the same, but the new TIG results in a different inertial burn attitude. Unlike an inertial TIG slip where the burn attitude is inertially fixed, for an LVLH TIG slip, the Orbiter's burn attitude is changed to the new inertial attitude when the burn is executed.⁶ Despite this difference in the maneuvers, the process to determine the maximum TIG slip is the same. Figure 8 shows the nominal trajectory (labeled 'NOM'), 1-minute (labeled '1'), 2-minute (labeled '2'), and 3-minute (labeled '3') LVLH TIG slips of the NC burn. The propellant costs for each of the slip cases written in terms of ΔV in ft/sec are also included in Figure 8. Just as for the inertial TIG slip, the maximum LVLH TIG-slip duration is determined by evaluating the relative motion plots for a violation of the 4-nm constraint (shown as the solid gray line). For this example, the maximum LVLH TIG slip is slightly over 1-minute. To execute a 1-minute LVLH TIG slip, there is a cost of an additional 12 feet per second of ΔV over the nominal burn plan.

After both methods for executing the TIG slip are evaluated, the results are compared to select which method to use and to specify the maximum TIG-slip duration. If the results are equal for relative motion and propellant, the inertial TIG slip is preferred because it is easier for the crew to execute since the inertial burn attitude is unchanged. However, if the LVLH slip has a longer maximum duration or lower propellant costs, then it could be selected over the inertial TIG slip. The prototype will be used to determine the maximum duration for both inertial and LVLH TIG slips and provide a recommendation of the TIG-slip method to execute.

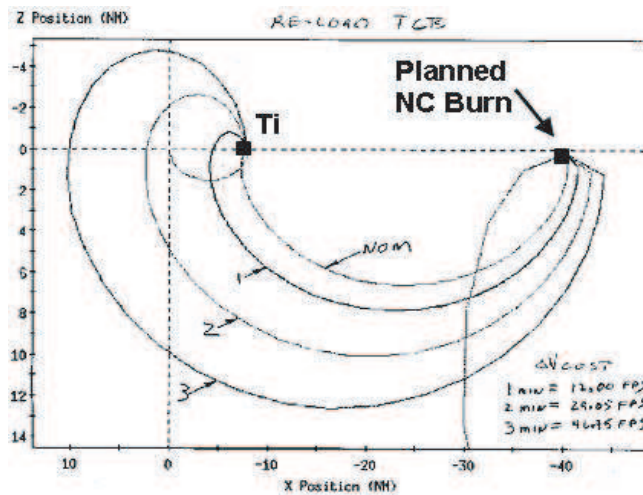


Figure 8. LVLH TIG slip

IV. Fuzzy Logic Decision-Making

The next step is to select an AI decision-making technique to use for prototyping the selected rendezvous functions. This section describes the results of the selection process. Candidate methods included, but were not limited to, neural networks, expert systems, and Fuzzy Logic (FL). The selection of the method depends heavily on the selected functions. The selected method should be compatible with rendezvous decision-making processes described in the previous section. This decision-making is based on flight rules and procedures, which must be properly modeled in the prototype. During the selection process, special considerations for human spaceflight must be addressed. In human spaceflight applications, safety of the crew is paramount and many steps are taken to ensure their safety. As a result, the operations of the vehicle are constantly being adjusted to maximize capability to ensure safety. For the prototype to be successful, it must have the flexibility to accommodate changes in the way the spacecraft is operated. Since the rendezvous functionality will not be fully automated, a human flight controller must be able to quickly and easily understand the output of the automated system. If the flight controller cannot understand the output, then they are at risk of incorrect action that could jeopardize the safety of the crew. In order to allow for regular updates to the automated software, the selected method should be simple enough so the verification and validation process is streamlined. This is particularly important given the rigorous testing standards used for human spacecraft.

Whereas both Expert Systems and FL are well-suited for modeling the selected rendezvous functions which are captured in flight rules and procedures, terms such as ‘slightly’ and ‘small’ are common in the procedures. Examples from the FDO handbook are given below:⁶

- ‘...it may be prudent to execute a Ti Delay burn...if the trajectory is just slightly outside limits.’
- ‘If a stable football has been achieved post Ti , and NCC delta-V is predicted to be small, then...consider waiving NCC...’⁶

These approximate terms cannot be easily modeled using binary logic but are well suited for modeling using FL. This indicates that FL can successfully model the flight rules and procedures for the selected rendezvous functions. FL also satisfies the criteria for ease in modification, thus accommodating future changes to operational procedures. The outputs are easily understood by human flight controllers since the models are based on natural-language terminology.

After surveying the decision-making methods described above, FL was chosen because it best satisfies the selection criteria. One concern with the FL techniques is the verification and validation of the software due to model complexity. Nonetheless, if the models remain at a reasonable level of complexity, this issue is manageable. Since the prototypes are intended to model individual tasks and not the entire decision-making process, there is little risk of prohibitive model complexity. This concern should be considered if these types

of models are accepted into wide use or are integrated into larger systems. Overall, FL is an excellent candidate for modeling the human decision-making for the selected rendezvous functionality.

V. Modeling Rendezvous Functions Using Fuzzy Logic

This chapter provides a brief description of FL, including an example of how it is used to model input-output relationships. The FL models used for TIG-slip planning are described in detail.

A. Fuzzy Logic

FL is a powerful technique that enables the mathematical representation of approximate terms such as ‘small’, ‘medium’, and ‘large’ with a continuous range over the closed interval, $[0,1]$. This technique, attributed to Zadeh, has become widely used for applications such as control systems, image processing, and to model human decision-making.¹² FL allows the modeling of relationships that are more complicated than binary logic (yes=1 and no=0). The foundation of FL is the concept of a ‘fuzzy set’ which allows intermediate values to be assigned, which fall between yes and no (true and false, medium and large, etc.). This concept is also known as multi-valued logic.

B. Modeling TIG-Slip Planning Using Fuzzy Logic

This section describes the FL models used to model the TIG-slip planning process. A brief description is provided that details the steps involved in the process. Then, the FL models used to complete the planning process are described in detail.

There are three separate FL models used to model the TIG-slip planning process. Two of the models are used to iteratively converge on the maximum TIG-slip duration; one is for the inertial TIG slip, and one is for the LVLH TIG slip. Both of these models are intended to emulate the way in which the human flight controller iteratively converges on the maximum TIG-slip duration. An initial guess is evaluated to determine how close the trajectory approaches the relative motion constraint. The distance from the constraint is provided as the input to the FL model. A small distance from the constraint will result in a small adjustment to the TIG-slip duration, and a large distance will result in a large adjustment. These models are run iteratively until they converge within a desired tolerance on duration. The third FL model is used to compare the two types of TIG slip based on the comparison of maximum TIG-slip duration and additional propellant cost. The output of this model is a recommendation of the TIG-slip method to execute. This model also includes a bias toward the inertial TIG-slip method, so if the TIG slip types are equal, the inertial TIG slip is recommended.

1. Inertial TIG-slip Iteration Model

The input for the inertial TIG-slip iteration model is called the ‘position-offset’, in nautical miles. The position-offset is measured as the difference between the maximum relative motion between the NC and Ti points for the TIG slip trajectory and the 4-nm relative-motion constraint (equation 5.1).

$$\text{position-offset} = \text{max relative position} + 4 \text{ nm} \quad (1)$$

This distance is shown for a 30-second inertial TIG slip in Figure 9 and a 180-second inertial TIG slip in Figure 10. The input values to the TIG slips are -2.7 nm for the 30 second inertial TIG slip and 4.8 nm for the 180 seconds inertial TIG slip. It is clear that negative values of position-offset correspond to trajectories that do not reach the constraint and thus can be additionally slipped. Positive values of position-offset have exceeded the constraint, and the TIG-slip duration must be reduced to satisfy the constraint.

The input membership functions of the inertial TIG-slip iteration model describe the position offset using the terms ‘Negative-Large’, ‘Negative-Small’, ‘Zero’, ‘Positive-Small’, and ‘Positive-Large’. The membership functions used to describe these linguistic terms are shown in Figure 11. The input range is limited to ± 6 nm to reflect a reasonable range of position-offset values. The membership functions for both the inputs and outputs were shaped by an empirical process to result in a successful iteration process for the inertial TIG-slip method.

The output of the inertial TIG-slip iteration model is a ‘time-delta’ from the TIG-slip duration for the previous iteration. The output range is between ± 80 seconds. The output membership functions use

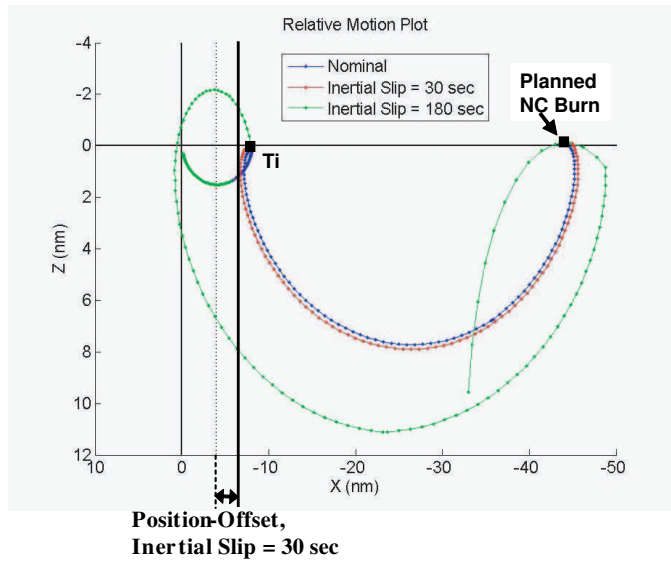


Figure 9. Inertial TIG-slip of 30 seconds, Position-Offset

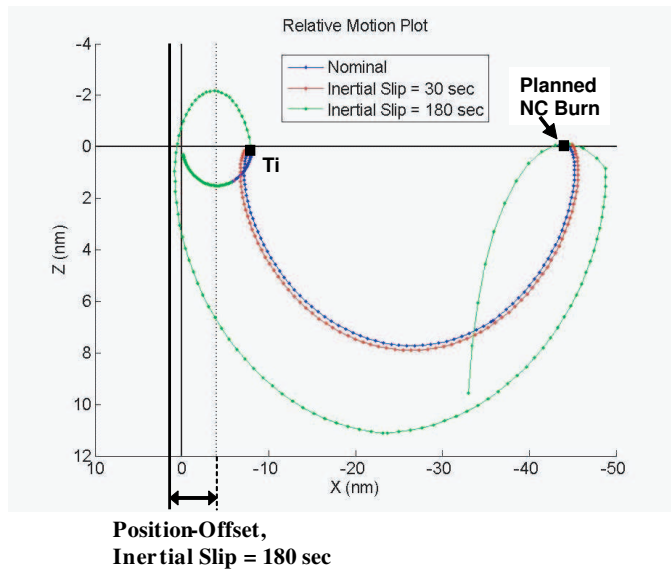


Figure 10. Inertial TIG-slip of 180 seconds, Position-Offset

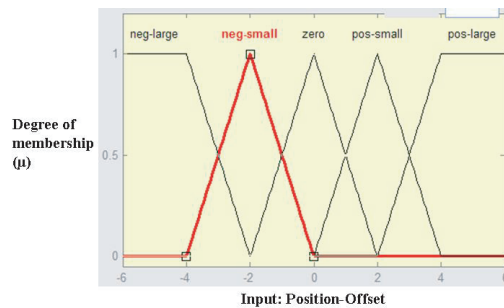


Figure 11. Inertial TIG-slip Iteration Model, Input Membership Functions

the same linguistic terms as the input membership functions, ‘Negative-Large’, ‘Negative-Small’, ‘Zero’, ‘Positive-Small’, and ‘Positive-Large’. The membership functions used to describe these linguistic terms are shown in Figure 12.

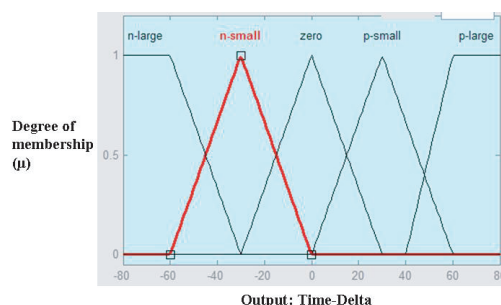


Figure 12. Inertial TIG-slip Iteration Model, Output Membership Functions

The rules for the inertial TIG-slip iteration model are described in Table 1. Since a negative position-offset allows an increase in the duration of the TIG slip, as described above, a negative position offset should result in a positive time-delta and vice versa. The rules reflect this relationship and result in small time changes for small offsets and large time changes for large offsets.

The complete model consists of the input and output membership functions and the rules. The result is an input-output mapping used to modify the TIG-slip duration by the time-delta output. Figure 13 shows the relationship between a current position-offset and the resulting time-delta used in the iteration process. The relationship is approximately linear between position-offsets of ± 4 nm, with smaller position-offsets resulting in smaller time-deltas, as desired. For inputs that exceed ± 4 nm, the output is a constant maximum time-delta of ± 65 seconds. This is the upper limit of reasonable time-deltas for the inertial TIG slips based upon empirical analysis. This input-output mapping accurately reflects the desired behavior during the iteration process.

2. LVLH TIG-slip Iteration Model

The LVLH TIG slip and inertial TIG slip iteration models are identical except for differences in the output membership functions. The reason for this difference is that the dynamics of the LVLH TIG slip result in larger changes in relative motion than for an identical inertial TIG-slip case. This difference is evident in Figures 7 and 8, which show large relative motion differences between the inertial and LVLH TIG slips of identical durations. As a result, the output membership functions should reflect a smaller time-delta for a given position-offset than the inertial TIG-slip case.

The LVLH TIG-slip iteration model uses an identical input variable, position-offset, and membership functions as shown in Figure 11. The rules are also identical to the inertial TIG-slip iteration model, shown in Table 1. The output membership functions use the same linguistic terms as the input membership functions, ‘Negative-Large’, ‘Negative-Small’, ‘Zero’, ‘Positive-Small’, and ‘Positive-Large’. However, the output membership functions, shown in Figure 14, have different shapes to produce the desired input-output mapping.

Table 1. Rules for TIG-Slip Iteration Models

IF	THEN
Position-Offset is:	Time-Delta is:
Negative-Large	Positive-Large
Negative-Small	Positive-Small
Zero	Zero
Positive-Small	Negative-Small
Positive-Large	Negative-Large

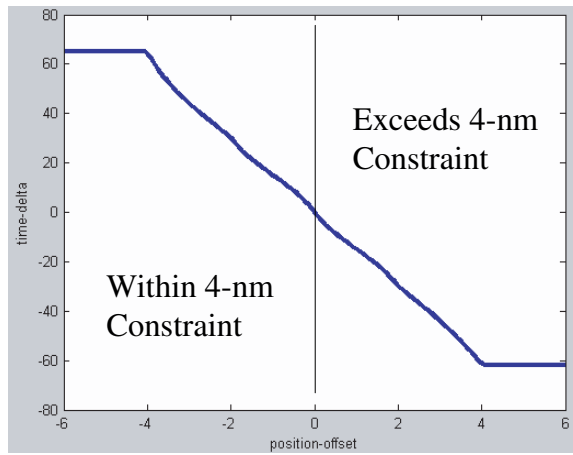


Figure 13. Inertial TIG-slip Iteration Model, Input-Output Mapping

The output membership functions are designed to prevent outputs that result in a violation of the relative motion constraint and will produce outputs that return trajectories to the acceptable side of the position constraint if a violation has occurred. This is accomplished by having small membership functions for positive time-deltas, which correspond to cases that are on the acceptable side of the relative motion constraint (negative position-offsets). There are also large membership functions for negative time-deltas, which correspond to violations of the relative motion constraint (positive position-offsets).

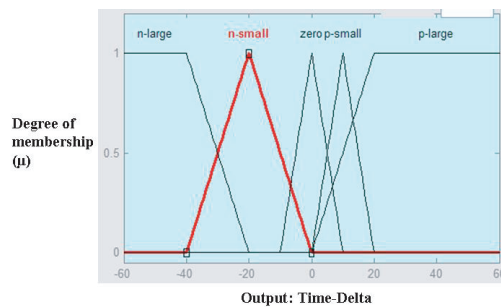


Figure 14. LVLH TIG-slip Iteration Model, Output Membership Functions

The resulting input-output mapping is shown in Figure 15. As desired, there is a gradual slope in time-delta for position-offsets with slightly negative values. This prevents cases that have not reached the relative-position constraint from exceeding the constraint. There is also a larger slope in time-delta for positive position-offsets, which causes cases that exceed the position constraint to return to the acceptable side of the constraint in the next iteration. This also prevents the iteration process from jumping back-and-forth over the boundary. Results of the iteration process for both inertial and LVLH TIG-slip cases can be found in the ‘Experiment Results’ chapter.

3. TIG Slip Comparison Model

Once the iteration process is complete for both TIG-slip methods, the results are compared using the TIG-slip comparison model described in this section. The output of this model is a value in the continuous interval $[-1,+1]$, with -1 corresponding to a strong recommendation for the inertial TIG-slip method and $+1$ corresponding to a strong recommendation for the LVLH TIG-slip method. This output is simply called ‘inertial-LVLH’. The inputs to this model are the difference in additional propellant and the difference in the maximum TIG-slip duration between the two methods. The input variables are called ‘propellant-difference’ and ‘time-difference’, respectively, which are defined in equations 5.2 and 5.3.

$$\text{propellant-difference} = \text{propellant}_{LVLH} - \text{propellant}_{inertial} \tag{2}$$

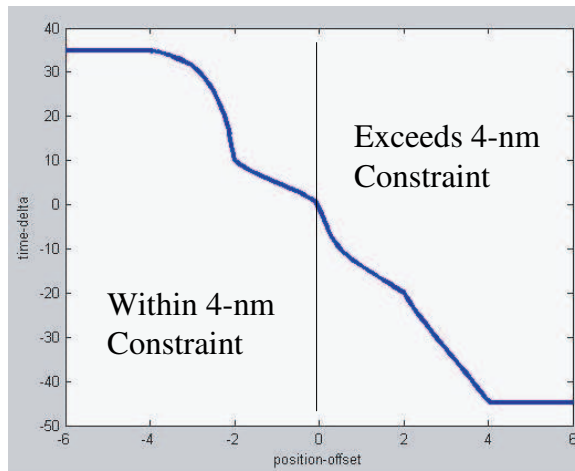


Figure 15. LVLH TIG-slip Iteration Model, Input-Output Mapping

$$\text{time-difference} = \text{time}_{LVLH} - \text{time}_{inertial} \quad (3)$$

A positive value of propellant-difference corresponds to a lower propellant cost for the inertial TIG-slip method, and a positive time-difference corresponds to a shorter maximum TIG-slip duration for the inertial TIG slip method.

The propellant-difference is modeled using membership functions with the linguistic terms ‘inertial-big-increase’, ‘inertial-small-increase’, ‘equal’, ‘LVLH-small-increase’, and ‘LVLH-big-increase’. These membership functions are shown in Figure 16. The input range of ± 20 ft/sec and the shape of the membership functions reflect a reasonable range of propellant differences determined by evaluating dispersed TIG-slip cases. For these cases, a small difference is considered to be between 0 and 10 ft/sec and a large difference is between 10 and 20 ft/sec.

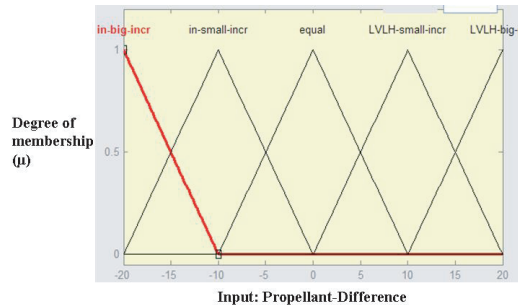


Figure 16. TIG-slip Comparison Model, Propellant Input Membership Functions

The time-difference is modeled using membership functions with the linguistic terms ‘inertial-more-time’ and ‘LVLH-more-time’. The input range for time-difference is ± 240 seconds (4 minutes). The membership functions for the time-difference are used to model the preference for the inertial TIG slip method since it is easier for the Shuttle crew to execute. This preference is built into the model by creating membership functions that are unequally balanced to favor the inertial TIG slip. In Figure 17, the membership function for LVLH-more-time does not start until an input value of 0 seconds and it does not cross the inertial-more-time membership function until a time-difference of 120 seconds.

The output membership functions for the the TIG-slip comparison model are shown in Figure 18. These membership functions use the linguistic terms ‘inertial-preference’, ‘inertial-slight-preference’, ‘equal’, ‘LVLH-slight-preference’, and ‘LVLH-preference’. The ‘inertial-preference’ and ‘LVLH-preference’ membership functions are designed to have a centroids at -1 and +1, respectively. This limits the output space to ± 1 and will result in an output of -1 for inertial TIG slip preference and +1 for LVLH TIG slip preference.

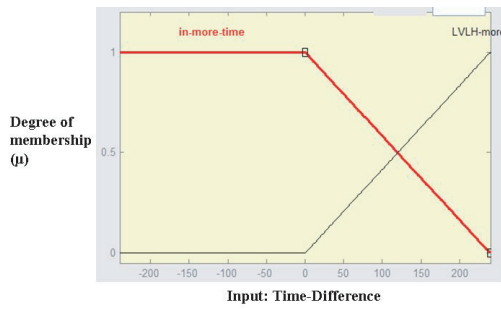


Figure 17. TIG-slip Comparison Model, Time Input Membership Functions

The membership functions that refer to a slight preference are sized to allow for small adjustments to the final result, where appropriate.

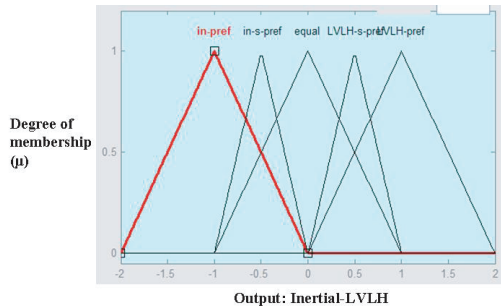


Figure 18. TIG-slip Comparison Model, Propellant Output Membership Functions

The rules used to provide the recommended TIG-slip method are captured in Table 2. These rules are intended to reflect how a human flight controller would compare the TIG-slip methods based on the difference in duration and additional propellant cost. For example, if the LVLH method results a big increase in propellant cost and the inertial method has a longer TIG-slip duration, the inertial TIG slip would be strongly recommended. The remainder of the rules capture the relative preference for all combinations of inputs.

The complete input-output mapping for the TIG-slip comparison model is shown in Figure 19. This model provides a continuous output surface over the entire input space. As expected, the surface has a minimum (maximum inertial preference) for a large propellant-difference (+20 ft/sec) and a large negative time-difference (-240 seconds, i.e., the inertial method provides 4 minutes of additional TIG-slip capability over the LVLH method). The maximum output value (maximum LVLH preference) corresponds to a large negative propellant-difference (-20 ft/sec) and a large time-difference (+240, i.e., the LVLH method provides 4 minutes of additional TIG-slip capability over the inertial method). The most interesting points of this input-output mapping are output values of zero, which denote the dividing line between recommending inertial and LVLH TIG-slip methods. The dashed line in Figure 20 shows the boundary between these recommendations. For cases with a longer allowable inertial TIG-slip duration (negative values of time-difference), the additional propellant cost of an inertial over an LVLH slip must exceed 10 ft/sec (-10 ft/sec propellant-difference) before an LVLH TIG slip is recommended. Another interesting feature is that the dividing line for equal propellant costs occurs at 120 seconds. These results confirm that the model reflects the desired bias toward inertial TIG slips.

VI. Experiment Design

This section will discuss the test cases and simulations used to evaluate the prototype rendezvous-planning functions. The objectives of the test cases, the assumptions, and the test environment are discussed for each prototype.

Table 2. Rules for TIG-slip comparison model

IF	AND	THEN
Propellant-Difference is:	Time-Difference is:	Inertial-LVLH is:
inertial-big-increase	inertial-more-time	LVLH-slight-preference
inertial-big-increase	LVLH-more-time	LVLH-preference
inertial-small-increase	inertial-more-time	equal
inertial-small-increase	LVLH-more-time	LVLH-slight-preference
equal	inertial-more-time	inertial-slight-preference
equal	LVLH-more-time	LVLH-slight-preference
LVLH-small-increase	inertial-more-time	inertial-slight-preference
LVLH-small-increase	LVLH-more-time	equal
LVLH-big-increase	inertial-more-time	inertial-preference
LVLH-big-increase	LVLH-more-time	inertial-slight-preference

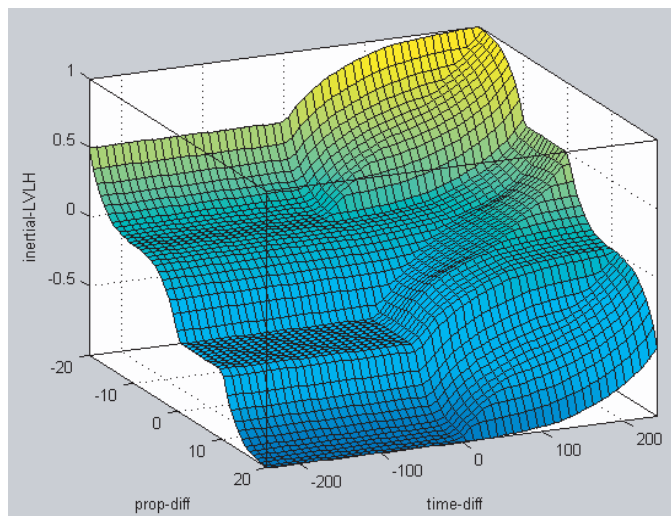


Figure 19. TIG-slip Comparison Model, Input-Output Mapping

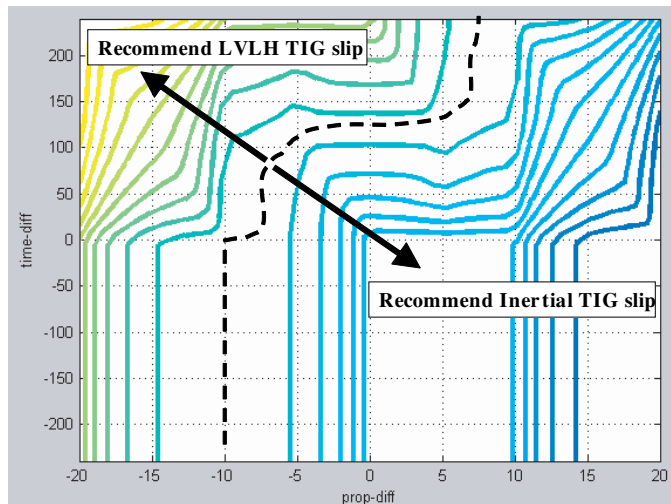


Figure 20. TIG-slip Comparison Model, Input-Output Mapping (Contour Plot)

A. TIG-Slip Planning

1. Objectives

The objective of the TIG-slip planning experiment is to evaluate the capabilities of the prototype by testing it in a realistic Space Shuttle rendezvous scenario. To be considered successful, the prototype must determine the maximum TIG-slip duration for both inertial and LVLH TIG-slip methods, compare the two methods, and provide a recommended TIG-slip method. The prototype must produce accurate results for both nominal and dispersed Shuttle rendezvous trajectories.

The success criteria for the calculation of the maximum inertial and LVLH TIG-slip durations is as follows: solutions must converge to within a reasonable number of iterations, the execution time of the algorithms should be minimized, and the resulting TIG-slip trajectory shall not violate the 4-nm position constraint. This criteria is summarized in Table 3. In addition, the results must include relative-motion plots for evaluation by a human user.

For the TIG-slip comparison model, the output must result in the recommendation of a TIG-slip method with a longer maximum TIG-slip duration and/or lower propellant cost. The specific input-output relationship must satisfy the intent of the TIG-slip comparison FL model described in the previous chapter. In general, the recommendation should be to use the inertial TIG-slip method unless the LVLH TIG-slip method provides a much longer TIG-slip duration (approximately 2-minutes longer), or has a much lower propellant cost (approximately 10 ft/sec less). The success criteria for the comparison method is simply that the recommended TIG-slip method is consistent with the FL model input-output mapping.

Table 3. TIG-Slip Planning Success Criteria

Criteria	Desired Value
Number of Iterations	< 10 iterations (Minimize)
Execution Time	< 1 minute (Minimize)
Maximum LVLH X-Position	< -4 nautical miles

2. Assumptions

This section describes the assumptions for the experiments used to evaluate the TIG-slip-planning prototype. For the prototype testing, a nominal rendezvous profile for a typical Shuttle-ISS mission is used. The test cases use the nominal rendezvous plan for the Space Shuttle mission designated as STS-110, which successfully rendezvoused with the ISS in April 2002. The TIG-slip-planning prototype is designed to determine the maximum TIG-slip duration for the NC burn. The portion of the trajectory that is evaluated in the experiment is shown in Figure 21, which includes the rendezvous trajectory from just prior to the NC burn and concludes at the Ti burn location. The NC burn is triggered based on time and will execute at the nominal TIG for the nominal trajectory. This burn will be delayed by the desired TIG slip duration and then executed as either an inertial TIG slip or LVLH TIG slip depending on the desired method. The burn plan also includes a correction burn, which is called NCC. The NCC burn is used to correct any errors and properly target the Ti point. For this experiment, it is assumed that the NCC burn is automatically targeted using the simulation environment described below.

The inputs to the TIG-slip-planning prototype are an initial state (nominal or dispersed initial conditions) and a nominal burn plan (in this case STS-110). The outputs of the experiment are the relative motion between the target (ISS) and chaser (Space Shuttle Orbiter) spacecraft, the recommended TIG-slip duration and method, and the additional propellant costs.

The accuracy requirement on the TIG-slip duration is assumed to be 2 seconds. Solutions that are more precise than 2 seconds far exceed the error inherent sources in this problem (such as navigation errors and the capability for the crew to execute a burn at a given TIG). Therefore, the iteration process will be terminated when the solutions for TIG-slip duration converge to within 2 seconds.

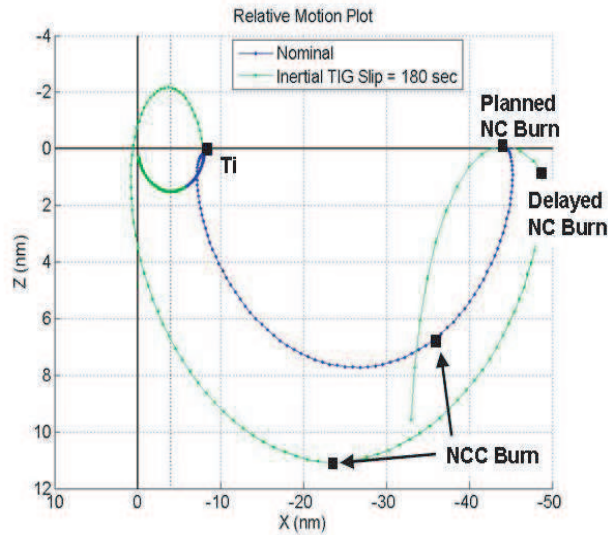


Figure 21. TIG-Slip Trajectory Example, Nominal and TIG-slip cases

3. Simulation Environment

The simulation environment and software components of the prototype are described in detail in this section. The simulation environment for the prototype is created using Matlab scripts. The Matlab scripts are used to call the FL models and trajectory routines.

The relative motion trajectories are computed using a NASA developed tool called ‘Platform Independent Software Components for the Exploration of Space’ (PISCES). This is a Java-based application, which includes many of the trajectory planning tools used by NASA mission planners and flight controllers to plan and execute spacecraft rendezvous. The PISCES environment consists of a graphical interface as well as compiled Java libraries. The TIG-slip-planning prototype uses Matlab to call the PISCES Java libraries. These PISCES libraries are used to handle the execution of the relative-motion trajectories.

The process for executing the TIG-slip-planning prototype is outlined in Figures 22 and 23. These figures show flow-charts for the TIG-slip planning routines called in Matlab. The functions are color-coded to indicate if the step is a PISCES trajectory computation, a Matlab routine, or a FL model. Also indicated on the flow-charts are the inputs and outputs for each function.

When determining the maximum TIG slip, the first step is to execute the nominal trajectory (Figure 22). The nominal trajectory parameters will be used to create the TIG-slip trajectories. Once the nominal trajectory has been executed, the maximum TIG-slip durations are computed for the inertial and LVLH TIG-slip methods.

The procedure for computing the inertial and LVLH TIG-slip durations are identical. The only differences are the type of TIG slip executed by PISCES (inertial or LVLH) and the FL model used to determine the TIG-slip duration for each iteration. The procedure for the inertial TIG-slip method is shown in Figure 23. The ‘Inertial TIG-slip Iteration’ FL model is called with the current value of ‘MAX_X_POSITION’ as an input, which is the location relative to the 4-nm position constraint. The output of the FL model is ‘DELTA_TIME’, which is the amount the TIG-slip duration should be adjusted based on the proximity of the relative trajectory to the 4-nm constraint. This value is added to the previous TIG-slip duration (TIME_OFFSET) to determine the new TIG-slip duration. Next, the relative motion trajectory is calculated for the new TIG-slip duration using PISCES (‘Execute TIG-slip Trajectory’). The outputs of the PISCES simulation are the new value of MAX_X_POSITION and the additional propellant cost over the nominal trajectory. The iteration process continues until the DELTA_TIME value converges to an increment that is less than 2 seconds, assuming that the position constraint is also satisfied (MAX_X_POSITION is less than -4 nm). If the position constraint is not satisfied, then the iteration continues until acceptable relative motion is achieved. The FL models for the inertial and LVLH iteration process are sized to provide an efficient iteration process.

After the maximum TIG-slip durations are computed for both inertial and LVLH methods, the outputs are passed to the TIG-slip comparison model. The ‘TIG Slip Comparison Model’ is a FL model that compares the results of the inertial and LVLH TIG-slip methods and recommends one method. For negative output values, the inertial TIG-slip is recommended, and for positive outputs the LVLH TIG-slip is recommended. The magnitude of the output is a measure of the strength of the recommendation, with a maximum magnitude of ± 1.0 . The results of the prototype test cases and evaluation are captured in Chapter VII, ‘Experiment Results’.

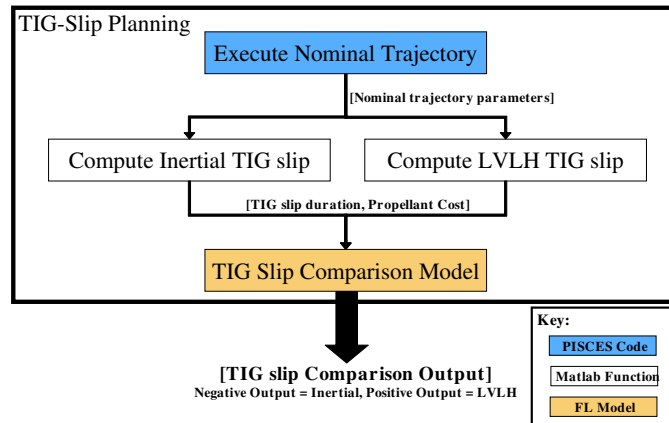


Figure 22. TIG-Slip Planning Flow-Chart

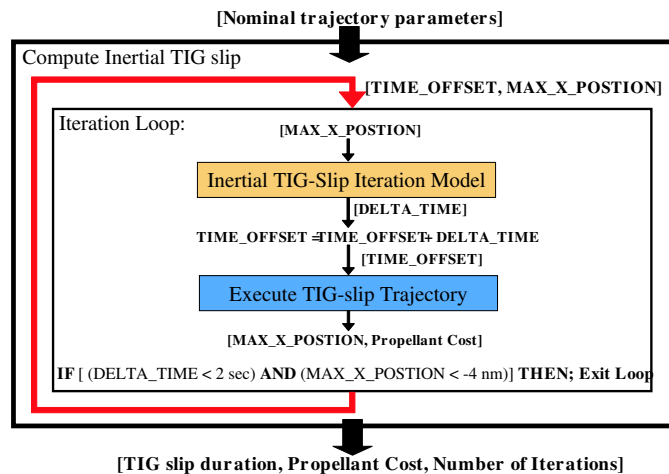


Figure 23. Compute Inertial TIG-Slip, Flow-Chart

B. Hardware and Software Configuration

Table 4 details the hardware and software configurations used for the development and testing of both prototypes.

VII. Experimental Results

A. TIG-Slip Planning

The results of the TIG-slip planning prototype are detailed in this section. The TIG-slip duration and additional ΔV costs are discussed for the inertial and LVLH TIG-slip cases for a non-dispersed nominal trajectory. The TIG-slip comparison model is used to recommend the type of TIG slip based on the inertial and LVLH TIG-slip results for the nominal trajectory. Results are also shown for cases with dispersed initial

Table 4. Hardware and Software Configuration for Prototype Experiments

Computer:	Dell Latitude 610, PC Laptop
CPU Speed:	2.0 GHz
Memory (RAM):	1.0 GHz
Operating System:	Windows XP, 2002
Matlab:	Version 7.2 (Release R2006a)
Fuzzy Logic:	Matlab, FL Toolbox, Version 2.2.3
Java:	Sun Microsystems, Version 1.5

conditions to evaluate the robustness of the FL solution method for trajectory dispersions. The results of the prototype are then compared to existing methods used for TIG-slip planning to evaluate the prototype.

1. Results, Nominal Trajectory

For the nominal case, the maximum inertial TIG slip is 109 seconds, which results in an additional 10.7 ft/sec of additional ΔV over the nominal trajectory. Figure 24 shows plots of the nominal trajectory, the iteration trajectories, and the trajectory for the maximum inertial TIG slip that satisfies the 4 nm X-relative position constraint. This solution is consistent with the results of the manually computed inertial TIG slip shown in Figure 7. The solution was found after 5 iterations with a total Matlab execution time of 5.4 seconds.

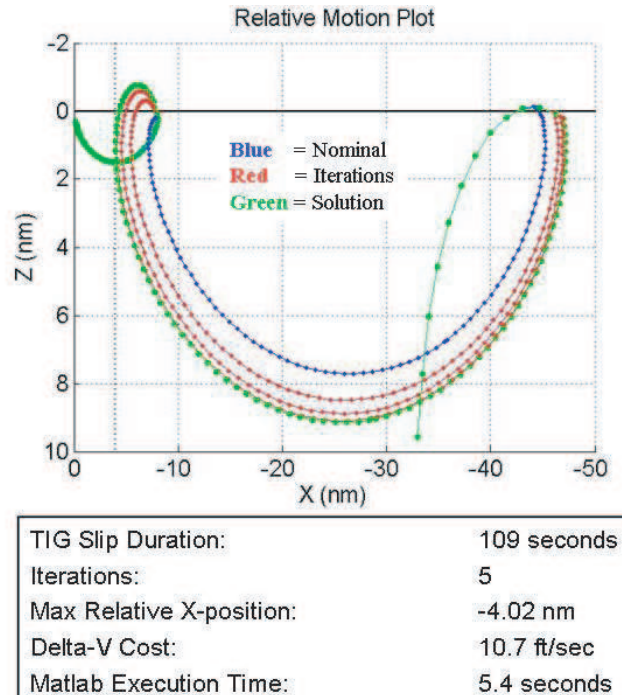


Figure 24. Inertial TIG-Slip Results, Nominal Trajectory

For the nominal case, the maximum LVLH TIG slip is 58 seconds, which results in an additional 9.6 ft/sec of additional ΔV over the nominal trajectory. Figure 25 shows plots of the nominal trajectory, the iteration trajectories, and the trajectory for the maximum LVLH TIG slip that satisfies the 4-nm X-relative position constraint. This solution is consistent with the results of the manually computed LVLH TIG slip shown in Figure 8. The solution was found after 3 iterations with a total Matlab execution time of 4.5 seconds.

A comparison of the maximum TIG-slip trajectories for inertial and LVLH cases is shown in Figure 26. In this figure, it is clear to see the difference in the trajectories where the longer slip duration of the inertial run

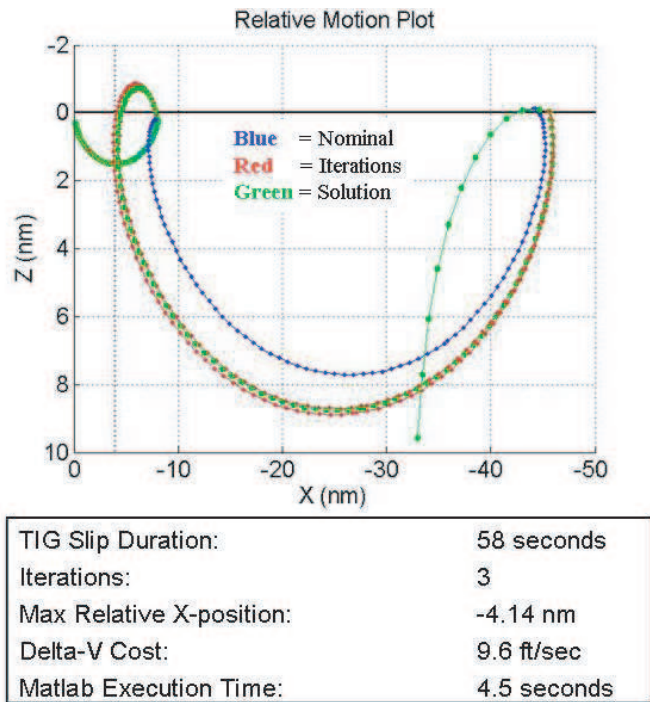


Figure 25. LVLH TIG-Slip Results, Nominal Trajectory

results in additional relative motion away from the target vehicle. However, as expected both trajectories satisfy the 4-nm X-relative position constraint indicated on the plot by the dashed lined.

The maximum durations for inertial and LVLH TIG slips and their corresponding ΔV costs are compared using the FL TIG-slip comparison model. The input to the comparison FL model is a difference in TIG slip duration of 51 seconds, favoring the inertial TIG slip and a difference in ΔV cost of 1.1 ft/sec, slightly favoring the LVLH TIG slip. The output of the model for these inputs is -0.33, which is a strong recommendation for the inertial TIG slip. For this case, the recommendation is that an inertial TIG slip of approximately 109 seconds is allowed with an expected ΔV cost of approximately 10.7 ft/sec. This recommendation is consistent with the TIG-slip method that would be recommended by the FDO for these TIG-slip results.

2. Results, Dispersed Trajectories

A set of dispersed trajectories is used in order to test the capability of the TIG-slip prototype. This set of test cases consists of 100 trajectories with randomly dispersed initial conditions, with a $1-\sigma$ distribution of 100 meters (m) in relative position and 0.1 m/sec in velocity. These dispersed cases are shown in Figure 27. For each of these dispersed cases, a maximum inertial and LVLH TIG-slip duration is calculated.

Figure 28 shows the maximum inertial TIG-slip trajectories calculated using the dispersed initial conditions shown in Figure 27. As expected all of the cases approach, but do not violate, the 4 nm X-relative position constraint. The maximum TIG-slip durations for these cases range from a minimum of 88 seconds to a maximum of 128 seconds. The mean TIG-slip duration is 109 seconds, which is equal to the TIG-slip duration for the nominal trajectory. Corresponding with these dispersed trajectories, the additional ΔV costs above the nominal trajectory is a minimum of 9.4 ft/sec, a maximum of 11 ft/sec, and an average of 10.5 ft/sec. For these dispersed runs, the inertial TIG-slip solutions were found in 5 iterations.

The results for the LVLH TIG slip with dispersed initial conditions are shown in Figure 29. As with the inertial results, all of the cases approach, but do not violate, the 4 nm X-relative position constraint. The maximum TIG-slip durations for these cases range from a minimum of 46 seconds and a maximum of 70 seconds. The mean TIG-slip duration is 58 seconds, which is approximately equal to the TIG-slip duration for the nominal trajectory. The range of additional ΔV over the nominal trajectories ranges from 7.9 ft/sec to 12.2 ft/sec with a mean of 9.9 ft/sec. These solutions were found in a minimum and maximum of 2 and 4 iterations, respectively. These results and the results above confirm that the prototype for calculating the

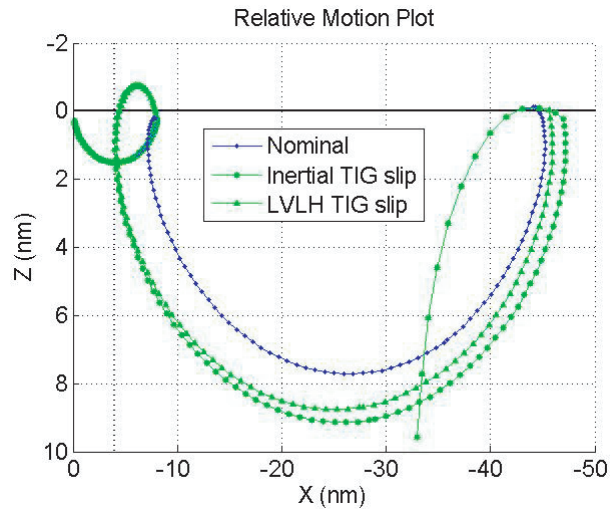


Figure 26. Inertial and LVLH Maximum TIG Slip Comparison, Nominal Trajectory

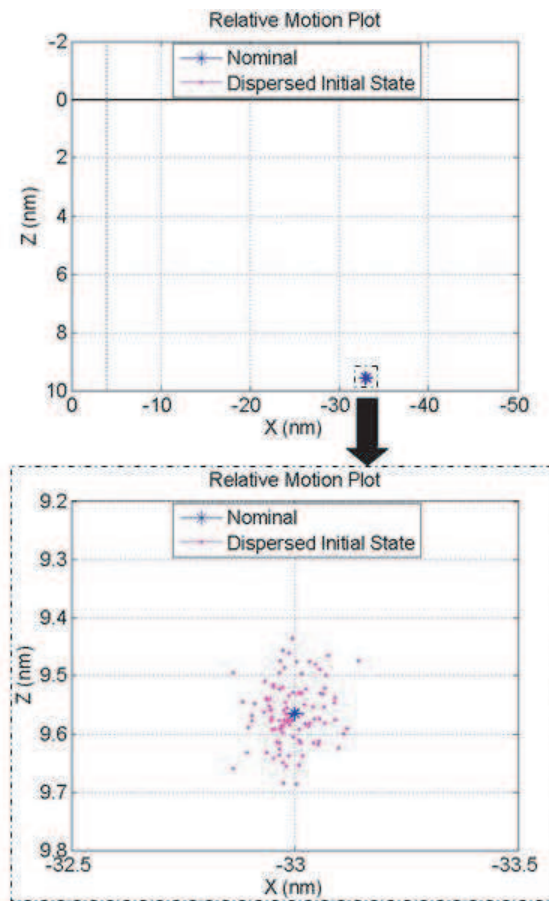


Figure 27. Dispersed Initial Conditions for NC TIG slip

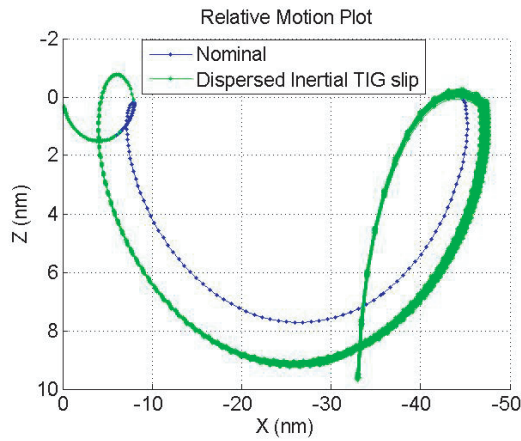


Figure 28. Inertial TIG slip for Dispersed Initial Conditions

maximum inertial and LVLH TIG-slip durations is capable of handling dispersed trajectories, which result in a wide range of TIG-slip durations.

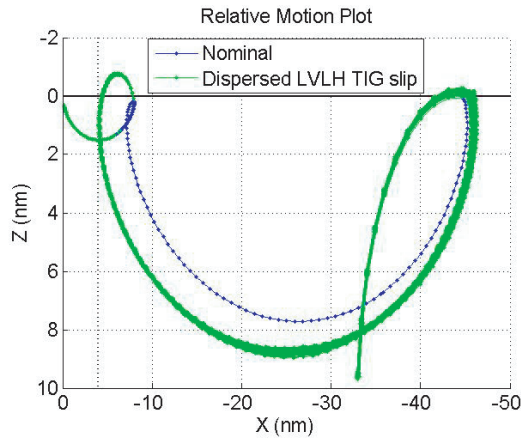


Figure 29. LVLH TIG slip for Dispersed Initial Conditions

Results from these inertial and LVLH TIG-slip calculations are then compared using the FL TIG-slip comparison model. All of the dispersed trajectory cases result in a longer maximum TIG-slip duration for the inertial TIG-slip method. The average inertial TIG slip is 51 seconds longer than the average LVLH TIG slip and none of the trajectories have a longer LVLH than inertial TIG slip. Despite the difference in TIG-slip durations, both TIG-slip methods have similar ΔV costs. The mean ΔV cost for inertial is 1.1 ft/sec larger than the mean for LVLH TIG slips. Based on these results for the dispersed cases the FL TIG-slip comparison model properly recommends an inertial TIG slip for all of the dispersed trajectory cases.

3. Comparison to Existing Methods

Recall that the existing method for determining the maximum duration and type of TIG slip involves a human flight controller iteratively running trajectory algorithms.⁶ The flight controller computes the maximum TIG-slip duration and associated ΔV cost for the inertial and LVLH TIG slips. Then, the recommended TIG-slip type, duration, and ΔV cost is passed along to the Flight Dynamics Officer (FDO), who is in charge of the rendezvous maneuvers. These recommendations are typically approximate values, such as ‘inertial TIG slip of slightly less than 2-minutes’. Figures 7 and 8 show this analysis and the hand written markings used to denote the nominal trajectory (NOM), 1-minute (1), 2-minute (2), and 3-minute (3) TIG slips. Also included in these figures are the propellant costs for each of the slips written in terms of ΔV in ft/sec. As part of this analysis, the flight controller takes into account the bias toward executing an inertial TIG slip

over an LVLH TIG slip. This preference is reflected by recommending an inertial TIG slip unless the LVLH TIG slip provides around 2 minutes of additional TIG slip capability. The LVLH TIG slip could also be recommended if it provides significant propellant savings over the inertial TIG slip. This analysis typically requires at least a few minutes to execute all of the runs and evaluate the results.

The TIG-slip prototype automates the determination of maximum TIG slip for the NC (phase change) burn shown in Figure 3. This method is able to quickly converge to the maximum TIG-slip durations for inertial and LVLH TIG slips. The iteration process results in very exact TIG-slip durations that actually are more precise than necessary. The iterations are terminated when the outputs converge to within 2-seconds of the TIG-slip duration that would result in relative motion that just satisfies the 4 nm X-relative position constraint. By providing the FDO with this very precise TIG-slip duration, they can decide how much conservatism they want to apply to the solution.

The success criteria for the prototype calls for the minimize the number of iterations. However, FL iteration method does not converge in the optimal number of iterations. Typical iteration numbers for the prototype are 5 iterations and 3 iterations for inertial and LVLH TIG slips, respectively. Since the execution time of the prototype is very quick, approximately 5 seconds, this is not an issue. A benefit of the FL iteration method is that it does not require an analytical model of the system dynamics which would be necessary for optimal convergence methods.

Once the TIG-slip durations are calculated, the durations and propellant costs are input into the FL TIG-slip comparison model. These inputs are used to determine the recommendation of TIG-slip method. This model takes into account the bias toward inertial TIG slips in its calculations. The output of this prototype is a value between -1 and 1, with negative numbers corresponding to a recommendation of an inertial TIG slip and positive numbers corresponding to a recommendation of an LVLH TIG slip. Numbers closer to the extrema of this range represent a stronger recommendation for that type of TIG slip. This allows the human flight controller to understand the strength of the recommendation when evaluating the output of the FL comparison model.

This prototype successfully models the process used to compute TIG-slip durations and determine which type of TIG slip to recommend. The results are actually more precise than the existing method in terms of TIG-slip durations. All of the data used to make a recommendation is provided to the human user including TIG-slip duration and ΔV costs for both TIG-slip methods, relative motion plots, and strength of the recommendation of the TIG-slip type. Since the data used in making the recommendation is output by the prototype, this implementation allows the human to evaluate the results and provide an alternate result, if necessary. This implementation matches the desired level of automation with the computer considered prime, with the human also making the calculations as a backup.

VIII. Conclusions

Prototypes of the selected Shuttle/ISS rendezvous decision-making task validate the feasibility of implementing higher levels of automation for such tasks. The TIG-slip-planning prototype automates the determination of the maximum TIG-slip duration for both inertial and LVLH TIG-slip methods and recommends the desired TIG-slip type producing accurate TIG-slip results that are comparable to existing methods but are calculated more quickly.

The results of the prototype confirm that the FLOAAT recommended level of automation is accurate. The prototype of the TIG-slip planning was successfully implemented to the desired level of automation. The computer provides a recommendation that can be used and verified by the human user before implementation. The results of this prototype indicated that the FLOAAT recommended level of automation is appropriate for this function.

The prototypes demonstrate that FL can be effectively used to model human decision-making used in spacecraft rendezvous. FL is well suited for the types of decisions made by human flight controllers, which are based on “rules-of-thumb” captured in the flight rules and procedures. Much of the success of the FL technique is due to its ability to capture approximate terms often used by humans. The FL iteration method used in TIG-slip planning demonstrates the capability of this technique to quickly and effectively converge on a solution without requiring an analytical model of the system dynamics. The prototype performs the iteration in a manner similar to how a human would perform the same function. By emulating the human iteration process, the chances of acceptance and trust in the automation are higher because the method is easy to understand and can be quickly adjusted. This method also provides outputs that can be easily

understood by a human user.

The methodology for prototyping rendezvous functions at higher levels of automation is judged to be a promising technique. The FLOAAT tool can be used to accurately identify functions that can be implemented at an increased level of automation. FL has many desirable attributes for modeling human decision-making, which make it an excellent candidate for additional spaceflight automation applications.

IX. Recommendations

The results and conclusions indicate areas for future work and improvements.

1. **TIG-slip planning:** Future test cases should evaluate the accuracy of the prototype for NC burn locations originating at different relative positions. The NC burn can be executed at ranges on the order of ± 20 nm from the nominal location of 40 nm. Executing these cases would additionally test the robustness of the prototype. In addition, the input-output mapping for the recommendation of TIG-slip method should be validated against additional Shuttle missions. The current relative assessment of propellant costs versus TIG-slip duration is notional and should be additionally refined.
2. **FLOAAT recommended level of automation:** The results of this research encompass only a small portion of the complete set of rendezvous planning functions. Additional prototyping should be used to provide additional confirmation of the accuracy of the FLOAAT specified levels of automation.

X. Acknowledgments

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