Pterodactyl: Trade Study for an Integrated Control System Design of a Mechanically Deployable Entry Vehicle

Antonella I. Alunni[*], Sarah N. D'Souza[†], Bryan C. Yount[‡], Wendy A. Okolo[§], and Benjamin W.L. Margolis[**], and Ben E. Nikaido[††]
NASA Ames Research Center, Moffett Field, CA 94035

Breanna J. Johnson[‡‡]
NASA Johnson Space Center, Houston, TX 77058

Jeffrey D. Barton[§§], Gabriel Lopez[***], and Lawrence S. Wolfarth[†††]
John Hopkins University Applied Physics Laboratory, Laurel, MD 20723

Zane B. Hays[‡‡‡]
AMA, Inc., Moffett Field, CA 94035

This paper presents the trade study method used to evaluate and downselect from a set of guidance and control (G&C) system designs for a mechanically Deployable Entry Vehicle (DEV). The Pterodactyl project was prompted by the challenge to develop an effective G&C system for a vehicle without a backshell, which is the case for DEVs. For the DEV, the project assumed a specific aeroshell geometry pertaining to an Adaptable, Deployable Entry and Placement Technology (ADEPT) vehicle, which was successfully developed by NASA's Space Technology Mission Directorate (STMD) prior to this study. The Pterodactyl project designed three different entry G&C systems for precision targeting. This paper details the Figures of Merit (FOMs) and metrics used during the course of the project's G&C system assessment. The relative importance of the FOMs was determined from the Analytic Hierarchy Process (AHP), which was used to develop weights that were combined with quantitative design metrics and engineering judgement to rank the G&C systems against one another. This systematic method takes into consideration the project's input while simultaneously reducing unintentional judgement bias and ultimately was used to select a single G&C design for the project to pursue in the next design phase.

---

[*] Aerospace Engineer, Entry Systems and Vehicle Development Branch, NASA ARC/TSS
[†] Principal Investigator, Systems Analysis Office, NASA ARC/AA
[‡] Experimental Facility Developer, Engineering Systems Division, NASA ARC/RE
[§] Aerospace Research Engineer, Intelligent Systems Division, NASA ARC/TI
[**] Graduate Pathways Student, Systems Analysis Office, NASA ARC/AA
[††] Aerospace Flight Systems Engineer, Systems Analysis Office, NASA ARC/AA
[‡‡] Aerospace Engineer, Flight Mechanics and Trajectory Design Branch, NASA JSC/EG5
[§§] Guidance & Control Engineer, Force Projection Sector, JHU/APL
[***] Systems Engineer, Space Exploration Sector, JHU/APL
[†††] Parametric Resource Analyst, Space Exploration Sector, JHU/APL
[‡‡‡] Research Assistant, Analytical Mechanics Associates, Inc.

I. Nomenclature

CI = Consistency Index for Analytic Hierarchy Process
CR = Consistency Ratio for Analytic Hierarchy Process
m_{PBV} = Pterodactyl Baseline Vehicle mass, kg
m_{CS} = control system mass, kg
m_{total} = total Pterodactyl Baseline Vehicle mass including control system, kg
mf_{CS} = control system mass fraction
n = order of matrix for Analytic Hierarchy Process
$\bar{q}$ = dynamic pressure, Pa
$\bar{q}_{max}$ = maximum dynamic pressure, Pa
RI = Random Index for Analytic Hierarchy Process
α = angle of attack, deg
β = sideslip angle, deg
β_{max} = maximum sideslip angle, deg
λ_{max} = principal eigenvalue of matrix for Analytic Hierarchy Process
σ = bank angle, deg
$\ddot{\sigma}_{max}$ = maximum bank acceleration, deg/s^2

II. Introduction

Current guidance and control (G&C) for hypersonic entry has been adapted for use by rigid entry vehicles, which usually rely on reaction control systems (RCS) installed on the backshell to control the bank angle of the vehicle. RCS thrusters are placed sufficiently far away from the center of mass to maintain adequate control authority for entry, descent, and landing (EDL), in locations where the thruster exhaust avoids sensitive areas of the vehicle such as the payload. With rigid aeroshells and RCS, robotic missions to Mars have succeeded in landing up to 1 metric ton (mt) payloads, and near-term Mars mission architectures may be capable of landing payloads up to 2 mt, based on deceleration limits of state-of-the-art EDL technologies.[1] In contrast, future human Mars missions will require 15-40 mt landed mass.[2] Safely landing payloads of this magnitude is considered unachievable by conventional EDL means, prompting a paradigm shift in EDL technologies to deliver higher payload mass precisely, reliably, and affordably.[3]

Deployable Entry Vehicles (DEVs) are potentially enabling technologies that permit a large aeroshell to be stowed, meeting the volume constraints of currently available launch vehicles, and later deployed to provide a low ballistic coefficient entry system capable of landing heavy payloads on Mars. Unlike conventional rigid entry vehicles, DEVs have no backshell, which poses a challenge with regard to the design and integration of G&C systems such as RCS. So, new ways of providing G&C to DEVs need to be explored and demonstrated on a smaller scale, conceivably capitalizing on interest in lunar sample return,[4] before pursuing ambitious Mars mission applications. Consequently, NASA's Space Technology Mission Directorate (STMD) has supported an array of efforts including Pterodactyl, which has been funded since 2018. Pterodactyl is a project that aims to investigate G&C systems that can be feasibly integrated with DEVs and usher in a capability that is compatible with a stowed DEV, has low mass fraction, and enables steering to a precise location with the implied added benefits of reliability and reduced operational costs.

Pterodactyl selected a version of Adaptable, Deployable Entry and Placement Technology (ADEPT) called Lifting Nano-ADEPT (LNA) for the project's preliminary studies to leverage previous efforts on this type of DEV.[5] ADEPT is a mechanically deployable decelerator that has demonstrated acceptable deployment performance and supersonic stability without active control during the Sounding Rocket One (SR-1) flight test.[6] ADEPT relies on a 3D woven carbon fabric that is flexible enough to stow for launch and structurally and thermally robust enough for entry. LNA is an asymmetric variant of ADEPT that was developed during a 2016 NASA Center Innovation Fund study, which explored subsystem integration of avionics, deployment substructures, and volume allocations for potential de-orbit, descent, and landing systems.[7] This past work on LNA served as the starting point for the Pterodactyl Baseline Vehicle (PBV), which has a 1 m deployed diameter and is illustrated in Figure 1.

Furthermore, Pterodactyl considered a lunar return mission as outlined by D'Souza[8] to understand how the G&C designs could manage high aerodynamic loads and heating rates resulting from high Earth entry speeds down to descent initiation at Mach 2. A peak heat flux of 250 W/cm^2 was assumed based on the proven capability of the carbon fabric, and g-loads below 15 g's were considered based on anticipated payload sensitivity to deceleration loads. Additionally, a secondary payload envelope on the Aft Bulkhead Carrier (ABC) of a Centaur V was employed to develop an understanding of mass and volume for G&C designs, resulting in an assumed volume of 0.5 m x 0.5 m x 0.6 m and mass of 77 kg for the PBV.

The initial scope of Pterodactyl's work was strictly focused on the design and evaluation of three independent G&C configurations, illustrated in Figure 2. The Flap Control System (FCS) comprises eight flared control surfaces that hinge into and out of the flow at the vehicle's rib tips to modulate aerodynamic forces and moments. The Mass Movement Control System (MMCS) comprises eight mass blocks that travel along the vehicle's ribs to produce shifts in center of gravity. Both of these configurations are characterized by their ability to provide non-propulsive control to track α-β or σ guidance commands, and both configurations were designed to integrate the maximum control capability that could be packaged into their respective hardware. The RCS comprises four hydrazine thrusters mounted at the vehicle's lateral ribs to provide adequate impulse to track σ guidance commands. All configurations were assessed with respect to mechanical systems, aerodynamics, aeroheating, entry guidance, trajectory design development, stability analysis, control design, and thermal protection system (TPS) analysis to develop a single point design for each G&C configuration. Methodologies and results from those analyses are reported in recent works.[9, 10, 11, 12, 13]

This paper presents the trade study conducted to assess all three G&C designs and subsequently downselect a single configuration for further analysis.

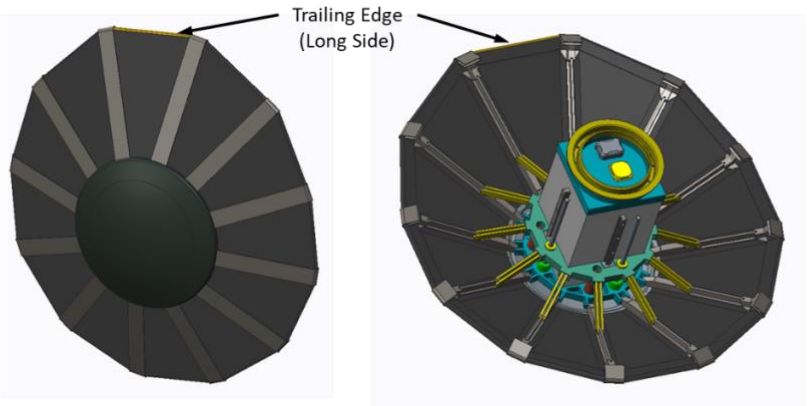
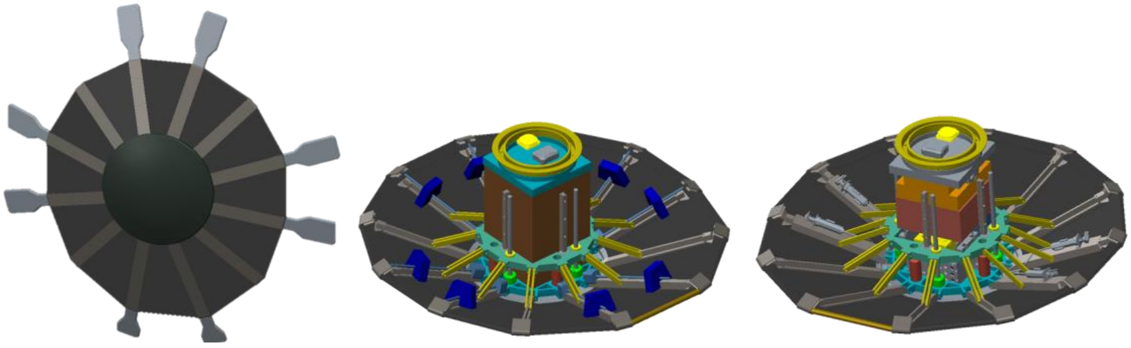


Figure 1. Windward (left) and leeward (right) views of the PBV design used in the investigation



(a) **(b)** **(c)**

Figure 2. Vehicle design with three G&C configurations evaluated in Pterodactyl: (a) FCS, (b) MMCS, and (c) RCS

III. Trade Study Overview

The following discussion codifies the framework Pterodactyl used to structure its trade study analysis of the three G&C designs. Important principles for evaluating the control system design results are reviewed, and decision-making approaches used to ultimately guide downselection are summarized.

A. Figures of Merit

Developing a technical understanding of precision landing innovations for DEVs is most imperative to Pterodactyl. The project also deems it important to establish an early awareness of what is viable in terms of cost and risk to develop technologies that are relevant to future missions. Therefore, the Pterodactyl trade study began with an assessment of Figures of Merit (FOMs) representing performance and effectiveness, affordability and life cycle cost, and safety and mission success to discern the trade-offs inherent in the FCS, MMCS, and RCS designs. The FOMs, listed in Table 1, were identified and their definitions were refined using input solicited from the team's experts and primary stakeholder, NASA's STMD EDL Principal Technologist. FOMs were also decomposed into quantitative and qualitative criteria to effectively analyze each configuration, as described in Section C.

Table 1. Summary of Pterodactyl FOMs

FOM Category	FOM	FOM Definition
Performance and Effectiveness	Control System Capability	Ability to successfully track guidance commands with respect to mechanical and G&C design limits across varying dynamic pressures expected for the assumed lunar return mission
Performance and Effectiveness	Control System Mass Fraction	Ability to successfully land a payload with respect to mechanical design limits for the lunar return mission
Performance and Effectiveness	Packaging / Stowage Efficiency	Ability to successfully conform to vehicle payload accommodation volume when stowed during launch and cruise
Affordability and Life Cycle Cost	Technology Development Cost	Cost to develop required technologies to TRL 6, beyond the scope of the project
Safety and Mission Success	Control System Reliability	Likelihood that the control system meets performance requirements during the EDL phases of the lunar return mission
Safety and Mission Success	Mission Reliability	Likelihood that the control system meets performance requirements before, during, and after the EDL phases of the lunar return mission

In the performance and effectiveness category, three FOMs were identified: control system capability, control system mass fraction, and packaging and stowage efficiency. Control system capability is defined as the ability to successfully track guidance commands with respect to mechanical design limits, as described by Yount,[14] and G&C design limits, as described by Johnson,[15] across varying dynamic pressures that are expected for the lunar return mission assumed for this study. This is the most critical FOM because the primary motivation of this project is to introduce and integrate a precision landing capability to a DEV with better than or equal to existing targeting accuracy as demonstrated by Mars Science Laboratory, which landed within 3 km of its target.[16]

Initially, the team explored Uncoupled Range Control (URC) for the FCS and MMCS designs to use α modulation to control downrange and β modulation to control crossrange. During the course of this investigation, simulations showed that the vehicle could only achieve small step-commands in α and β for a fixed σ.[17] The controls group discovered that a significant roll-yaw coupling induced a non-zero roll when a yaw moment was generated through the sideslip angle. These findings revealed the limited control authority of the FCS and MMCS designs and suggested that URC is unsuitable for the lunar return LNA with these control configurations. However, the controls group learned that the FCS and MMCS designs could use the asymmetric PBV's inherent roll-yaw coupling to successfully follow σ guidance commands, providing a more direct comparison with the heritage RCS system with σ control.[18] Therefore, design efforts shifted away from URC and tracking α-β and toward an approach that uses yaw to induce a roll tracking σ commands instead. Consequently, for this FOM, all three G&C configurations were compared with respect to

$$\ddot{\sigma}_{max} \text{ at } \bar{q} \text{ for G\&C activation and } \bar{q}_{max} \tag{1}$$

where $\ddot{\sigma}_{max}$ is the maximum bank acceleration each configuration could achieve and $\bar{q}$ is the dynamic pressure. In the case of FCS and MMCS, the maximum yaw capability, β_{max}, dictates the maximum roll capability because these two designs use roll-yaw coupling, so the following was also observed

$$\beta_{max} \text{ at } \bar{q} \text{ for G\&C activation and } \bar{q}_{max} \tag{2}$$

Control system mass fraction is defined as the ability to successfully land a payload with respect to mechanical design limits for the lunar return mission. The mechanical design for the LNA vehicle without a control system was used to generate a mass estimate of the PBV. After mechanical systems for the FCS, MMCS, and RCS configurations were fully developed, the ratio of control system mass, m_{CS}, to PBV mass, m_{PBV}, was used to express the control system mass fraction, mf_{CS}, of each design as follows,

$$mf_{CS} = \frac{m_{total} - m_{PBV}}{m_{PBV}} = \frac{m_{CS}}{m_{PBV}} \tag{3}$$

The packaging and stowage efficiency FOM is defined as the ability to successfully conform to the ABC secondary payload accommodation volume when stowed during launch and cruise. For this FOM, estimated percent volume remaining within the payload enclosure and ease of integrating control components were compared across each G&C configuration. At least 25% volume remaining was assumed desirable for reasonable packaging and stowage efficiency. Both control system mass fraction and packaging and stowage efficiency FOMs are important to ensure that the G&C configurations observe mission design constraints such as mass and volume, making the configurations attractive for mission adoption.

In the affordability and life cycle cost category, the technology development cost FOM is defined as the cost to deliver a control system technology to technology readiness level (TRL) 6. For each G&C configuration, a variety of ground testing and analysis campaigns were considered to determine a bottom-up cost estimate of initial technology maturation. Then, a parametric cost model of a flight test to achieve TRL 6 was developed for each G&C configuration and included major activities such as fabrication of a flight demonstration unit, launch services, and mission operations. The resulting cost estimates were combined and used to compare across all three designs. The estimated $6M cost to deliver an ADEPT vehicle for SR-1 was considered a relevant benchmark for flight test cost. Reaching TRL 6 is beyond the scope of the Pterodactyl project, so this FOM is less urgent but is nonetheless informative to anticipate barriers to entry for future missions.

Finally, in the safety and mission success category, two FOMS are identified: control system reliability and mission reliability. Control system reliability is defined as the likelihood that the control system meets performance requirements during the EDL phases of the lunar return mission, and mission reliability is defined as the likelihood that the control system meets performance requirements before, during, and after the EDL phases of the lunar return mission. Conceptual probability risk assessment (PRA) models were developed for each G&C configuration. Primary risk drivers that were identified include the failure of any combination of linear actuators that drive the mechanisms for the FCS and MMCS and the failure of any combination of hydrazine thrusters that provide the thrust impulse for the RCS. These risk drivers were captured in control system PRA models. Other risks that could occur during a mission life cycle were identified and preliminarily quantified in mission PRA models. Given the early development of Pterodactyl, these reliability FOMs are also less critical. However, they assure that risk awareness is developed as the new G&C systems are designed.

B. Analytic Hierarchy Process

Initially, the team had a basic sense of each FOM's relevance to Pterodactyl. For instance, control system capability stood out as the most important FOM bearing in mind Pterodactyl's fundamental aim to deliver precision landing solutions for DEVs. Mass fraction and packaging and stowage efficiency, which relate to how the configurations integrate with the DEV, were considered secondary at this point. Technology development cost and control system and mission reliabilities were viewed as least important. However, the project needed a rigorous way to quantify and quickly convey each FOM's impact on the eventual downselect decision. Consequently, the Analytic Hierarchy Process (AHP) proposed by Saaty[19] was used to determine how to rank and subsequently develop weights for the FOMs.

AHP is a systematic, multi-attribute decision analysis technique that takes into account team inputs while simultaneously reducing unintentional judgement bias. AHP enables the decomposition of a problem into its elements via a prioritization matrix, which is a positive, square matrix with rows and columns of elements ordered in the same sequence. Preferences are introduced directly into the matrix via pairwise comparisons of those elements using a ratio scale to express relative importance. Then linear algebra is applied to the resulting ratio judgements to establish prioritization weights.[20] With only six FOMs, Pterodactyl has a small decision space, so AHP proved to be a practical approach to clearly and quantitatively articulate values for the FOMs. Moreover, AHP is a methodology with NASA heritage in studies, projects, and proposed missions[21, 22] and has been widely used by other academic, public and private organizations.[23, 24, 25]

As a group, the Pterodactyl team conducted pairwise comparisons amongst the FOMs to rank preferences for G&C design development and to deliver corresponding FOM weights. Positions below the main diagonal of the AHP prioritization matrix, shown in Table 2, were filled by comparing the FOM in the associated row against the FOM in the associated column. The team employed the judgement scale in Table 3, which was derived from Saaty's nine-point fundamental scale of absolute numbers.[26] To maintain consistency in the prioritization matrix, positions above the main diagonal were automatically updated with reciprocal values corresponding to transpose positions in the matrix.

Table 2. AHP prioritization matrix for the Pterodactyl FOMs

	Control System Capability	Control System Mass Fraction	Packaging / Stowage Efficiency	Technology Development Cost	Control System Reliability	Mission Reliability
Control System Capability	1	2	5	9	9	9
Control System Mass Fraction	1/2	1	2	9	9	9
Packaging / Stowage Efficiency	1/5	1/2	1	5	5	5
Technology Development Cost	1/9	1/9	1/5	1	1	5
Control System Reliability	1/9	1/9	1/5	1	1	5
Mission Reliability	1/9	1/9	1/5	1/5	1/5	1

Table 3. Judgement scale (note intermediate values were used when compromise was needed)

Intensity of Importance	Definition
1/9	Extremely less important/preferred
1/7	Much, much less important/preferred
1/5	Much less important/preferred
1/3	Moderately less important/preferred
1	Equally important/preferred
3	Moderately more important/preferred
5	Much more important/preferred
7	Much, much more important/preferred
9	Extremely more important/preferred

The actual results from this group exercise are shown in Table 2. To illustrate an example of the team's judgement: the team regarded control system mass fraction as important; though the team, unanimously, valued control system capability the most. Hence, control system mass fraction is shown as slightly less important than control system capability, warranting a value of 1/2 in the corresponding matrix position. In turn, a value of 2 in the transpose position indicates that control system capability is therefore slightly more important than control system mass fraction.

Ultimately, the row geometric mean was normalized to produce the FOM weights portrayed in Figure 3. Performance and effectiveness FOMs capture the bulk of the total weight, as expected from a research and development project in its early stages. Furthermore, the FOM weights resulting from the AHP prioritization matrix clarifies and quantifies the project's preferences with regard to G&C design.

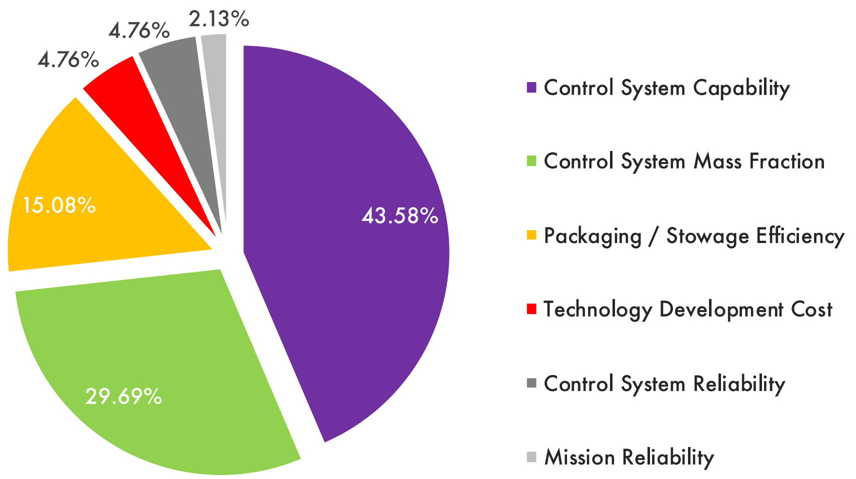


Figure 3. Pterodactyl FOM weights

Good agreement amongst the pairwise comparisons in the AHP prioritization matrix was subsequently verified before using the FOM weights further. In accordance with the method outlined by Saaty,[27] the principal eigenvalue, λ_{max}, of the matrix was used to solve for the Consistency Index, *CI*, where *n* is the order of the matrix in the following equation,

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

Then *CI* and Random Index, *RI*, were used to determine the Consistency Ratio, *CR*, of the matrix as follows,

$$CR = \frac{CI}{RI} \tag{5}$$

RI represents the mean *CI* of a large sample of randomly generated matrices (assuming the same judgement scale is used).[28] *RI* values are shown for a range of matrices in Table 4. $CR \leq 0.1$ indicates that acceptable judgement is expressed in the matrix. Given that Eqs. (4) and (5), when applied to the Pterodactyl AHP prioritization matrix, result in $CR = 0.09$, this method produces reasonable results.

Table 4. *RI(n)* values (where *n* = 6 for Pterodactyl investigation)

n	*RI*
1	0
2	0
3	0.5245
4	0.8815
5	1.1086
6	1.2479
7	1.3417
8	1.4056
9	1.4499
10	1.4854

C. Proxy Parameters and Control System Survey

To close out the trade study analysis, a survey was developed to finally rank the FCS, MMCS, and RCS designs. Ranking was accomplished using the FOM weights found in the previous section, proxy parameters identified for each FOM, and a high-level scale that ranged from inferior to exceptional and was founded on expectations of the G&C configurations.

The proxy parameters in Table 5 facilitated the collection of clear criteria when evaluating each design. For most FOMs, proxy parameters were readily identified. For example, the control system mass fraction FOM, defined earlier by Eq. (3) in Section A, serves as its own proxy parameter. For the technology development cost FOM, the proxy parameter is the total estimated cost to deliver technology supporting the G&C system for a flight test as estimated from the cost models. And for system and mission reliabilities, proxy parameters are the operational reliability and mission reliability, respectively, that were determined from the PRA.

Proxy parameters for the remaining FOMs required further scrutiny for effective evaluation of each G&C configuration. The control system capability FOM depended on two proxy parameters: targeting error between the final and desired terminal descent points, which is based on 99.9% miss distance, and level of control system capability, which categorizes a range of simulated controller performance outcomes. At worst, a configuration could be stymied by unresolved issues with tracking guidance commands, or the configuration's maximum bank acceleration could lag or only meet the bank acceleration requirement across the dynamic pressure regime used in design, justifying a classification of level 1. Guidance tracking that exceeds the bank acceleration requirement corresponds to level 2, and guidance tracking that highly exceeds the bank acceleration requirement corresponds to level 3.

The packaging and stowage efficiency FOM was also informed by two proxy parameters: stowed volume remaining in the payload enclosure, which is a straightforward measure based on the mechanical design, and level of integration ease, which classifies a range of qualitative integration estimates based on engineering judgment. At worst, integrating the DEV with a given configuration could be infeasible, impose major design issues, and require an extensive vehicle redesign. Such a design would deserve the lowest classification, level 1. A design with integration challenges that could be overcome without a major redesign effort corresponds to level 2, and level 3 corresponds to configurations considered moderately easy to integrate with the DEV. Though level of integration ease solely depends on expert opinion, all other proxy parameters rely on simulation and analysis and are therefore quantitative.

Table 5. Summary of proxy parameters for Pterodactyl FOMs

FOM	Proxy Parameter	Proxy Parameter Source
Control System Capability	Targeting error (in km) between the final and desired terminal descent points	Simulation & Analysis
	Level of control system capability (1: tracking is unresolved, lags, or meets, 2: tracking exceeds, 3: tracking far exceeds bank acceleration limit across dynamic pressure regime)	Simulation & Analysis
Control System Mass Fraction	mf_{CS}	Simulation & Analysis
Packaging / Stowage Efficiency	Stowed system volume remaining in Pterodactyl payload enclosure	Simulation & Analysis
	Level of integration ease (1: major issues, 2: challenging, 3: moderately easy)	Expert Opinion
Technology Development Cost	Estimated cost (in \$M) to deliver the control system technology for a flight test	Simulation & Analysis, Expert Opinion
Control System Reliability	Operational reliability	Simulation & Analysis
Mission Reliability	Mission reliability	Simulation & Analysis

A simple three-point scale was assumed to apply a score to the G&C configurations for each FOM, and the scale was additionally refined by the team to employ each aforementioned proxy parameter, p, and to distinctly communicate ratings. The trade study survey scale is shown in Table 6.

The scales for most FOMs vary directly with proxy parameters to reward the boldest designs with the highest scores. For control system capability, designs with final descent points beyond 3 km away from their desired terminal descent points automatically merit 1 on the survey scale. A maximum bank acceleration of 5 deg/s^2 was assumed for guidance simulations,[29] so configurations that merely meet or fall behind this assumed bank acceleration requirement in controller simulations also automatically score 1 on the survey scale for control system capability. Meanwhile, only configurations that far exceed the bank acceleration requirement across the dynamic pressure regime and exhibit a target ellipse smaller than 3 km are rewarded with the highest score of 3. Designs with less than 25% volume remaining or major integration issues merit a low score of 1, while designs with over 25% volume remaining and moderately easy integration score 3. For control system reliability and mission reliability, a 0.95 reliability threshold for developmental designs was assumed. So, configurations with reliability below 0.90 earn 1, while only designs with reliability above 0.95 deserve 3.

For control system mass fraction and technology development cost, scales vary inversely with proxy parameter to maintain the philosophy of rewarding the most capable designs with the highest scores. Designs with control system mass fractions above 0.30 are deemed too heavy and score 1, while only designs with low mass fractions below 0.20 qualify for a score of 3. Configurations with expensive technology development costs above \$20M only score 1, while configurations under \$10M score 3.

Ultimately, FOM weights were combined with the survey scores resulting in weighted total scores for each G&C design, which are summarized in the next section.

Table 6. Summary of trade study survey scale

FOM	Scale	Scale Definition
Control System Capability	1 = low	$p_1 > 3$ km or $p_2 = 1$
	2 = acceptable	$p_1 < 3$ km & $p_2 = 2$
	3 = high	$p_1 < 3$ km & $p_2 = 3$
Control System Mass Fraction	1 = high	$p > 0.30$
	2 = acceptable	$0.20 < p < 0.30$
	3 = low	$p < 0.20$
Packaging / Stowage Efficiency	1 = low	$p_1 <$ 25% vol remaining or $p_2 = 1$
	2 = acceptable	$p_1 >$ 25% vol remaining & $p_2 = 2$
	3 = high	$p_1 >$ 25% vol remaining & $p_2 = 3$
Technology Development Cost	1 = high	$p >$ \$20M
	2 = acceptable	\$10M $< p <$ \$20M
	3 = low	$p <$ \$10M
Control System Reliability	1 = low	$p < 0.90$
	2 = acceptable	$0.90 < p < 0.95$
	3 = high	$p > 0.95$
Mission Reliability	1 = low	$p < 0.90$
	2 = acceptable	$0.90 < p < 0.95$
	3 = high	$p > 0.95$

IV. Trade Study Downselection Results

The trade study survey of control systems described above was conducted after FCS, MMCS, and RCS designs were completed, as described in recently submitted works.[30, 31, 32, 33, 34] Design results and engineering judgments that are relevant to the trade study are collected in Table 7. Leading experts on the team used these results to rate each configuration in the trade study survey, which is outlined in Table 8.

For control system capability, guidance simulations showed that all three configurations had a target ellipse under 3 km.[35] So survey results were primarily inferred from maneuverability analyses that identified maximum bank acceleration of each design starting from G&C activation at a low dynamic pressure of 284 Pa to a maximum dynamic pressure of 2896 Pa.[36] For the FCS, the bank acceleration at low dynamic pressure is 11.5 deg/s^2, which exceeds the bank acceleration requirement assumed for this study. At maximum dynamic pressure, bank acceleration is 115 deg/s^2, which greatly exceeds the requirement, justifying a survey score of 3 for FCS. While the MMCS design exceeds the requirement with 13.8 deg/s^2 at maximum dynamic pressure, it was well below the requirement at 1.48 deg/s^2 at low pressure. Consequently, the MMCS has a survey score of 1. And the RCS design demonstrates a constant bank acceleration of 10.9 deg/s^2, exceeding the requirement across the pressure regime, and thus merits a 2 in the survey.

Table 7. Summary of Pterodactyl design results

FOM	Design Data	FCS	MMCS	RCS
Control System Capability	99.9% miss distance, km	0.64	1.10	0.93
Control System Capability	$\ddot{\sigma}_{max}$ at $\bar{q}$ = 284 Pa, deg/s^2	11.5	1.48	10.9
Control System Capability	$\ddot{\sigma}_{max}$ at $\bar{q}$ = 2896 Pa, deg/s^2	115	13.8	10.9
Control System Capability	β_{max} at $\bar{q}$ = 284 Pa, deg	-19.38	-7.32	-
Control System Capability	β_{max} at $\bar{q}$ = 2896 Pa, deg	-19.39	-7.40	-
Control System Mass Fraction	$m_{total,}$ kg	75.7	81.0	69.1
Control System Mass Fraction	$m_{CS,}$ kg	16.3	21.6	9.7
Control System Mass Fraction	mf_{CS}	0.27	0.36	0.16
Packaging / Stowage Efficiency	payload volume remaining, %	33	34	17
Packaging / Stowage Efficiency	level of integration ease	1	3	2
Technology Development Cost	technology maturation cost, $M	4.493	2.355	2.819
Technology Development Cost	flight test cost, $M	30.413	32.312	33.025
Technology Development Cost	total cost, $M	34.906	34.667	35.844
Control System Reliability	operational reliability	0.9404	0.9633	0.9743
Mission Reliability	mission reliability	0.8925	0.7556	0.9501

Table 8. Summary of Pterodactyl trade study survey results

FOM	Weight (from Fig. 3)	FCS	MMCS	RCS
Control System Capability	43.58%	3	1	2
Control System Mass Fraction	29.69%	2	1	3
Packaging / Stowage Efficiency	15.08%	1	3	1
Technology Development Cost	4.76%	1	1	1
Control System Reliability	4.76%	2	3	3
Mission Reliability	2.13%	1	1	3
Weighted Total		74%	47%	72%

For control system mass fraction and packaging and stowage efficiency, results were gathered from mechanical analysis.[37] For the FCS design, TPS sizing analysis was also considered to ensure survival of the flaps when exposed to the flow.[38] Control system mass fraction of FCS is 0.27, warranting a survey score of 2 for the second FOM. The sizing required for adequate control of MMCS resulted in notably heavy masses such that the total vehicle mass slightly exceeds the assumed ABC mass payload limit. Control system mass fraction of MMCS is 0.36, hence, it received a score of 1. The RCS design resulted in the lowest control system mass fraction, 0.16, which warranted a score of 3. The FCS design resulted in 33% volume remaining in the payload enclosure, but major integration issues are anticipated with the TPS. Therefore, the design earned a score of 1 for the third FOM. The MMCS design has the highest volume remaining, 34%, and is considered moderately easy to integrate; so, it earned a score of 3 for the third FOM. The RCS design includes an undesirably low amount of volume remaining, 17%, which introduces integration challenges with this design. So, it received a score of 1 for the third FOM.

For technology development cost, results were ascertained from cost modeling, which revealed that the estimated cost to initially mature technology for FCS is almost twice as high as it is for MMCS or RCS because of the additional TPS development required.[39] However, these differences are eclipsed by very expensive flight test costs. The estimated total cost to advance each configuration to TRL 6 is about $35M. Therefore, all three configurations earned a score of 1 for the fourth FOM.

For control system reliability and mission reliability, results were drawn from PRA.[40] The probability that the control system will operate successfully relies on failure data for the control mechanisms. Operational reliability is 0.9404 for FCS and 0.9633 for MMCS. RCS has the highest success probability, 0.9743, because the control mechanisms for RCS have flight heritage. The probability that the configuration will meet system performance throughout the mission takes into account operational reliability, maneuverability performance, and flight heritage. Mission reliability is 0.8925 for FCS, 0.7556 for MMCS, and highest, 0.9501, for RCS. MMCS has the lowest mission success probability because it displayed the worst maneuverability. For the fifth FOM, survey scores are 2 for FCS and 3 for MMCS and RCS. For the sixth FOM, survey scores are 1 for FCS and MMCS and 3 for RCS.

Lastly, these survey scores were combined with the FOM weights to generate a weighted total score, also listed in Table 8. The total survey score is dominated by the weighted scores of the three performance and effectiveness FOMs. As a result, the survey portrays FCS and RCS configurations with the highest weighted total scores, 74% and 72%, respectively, because they scored acceptably or higher in the top two FOMs. MMCS underperformed in these same FOMs; and, despite high scores in other lower weighted FOMs, this design trailed behind remarkably with a score of 47%.

Variations in the AHP matrix were investigated to analyze their impact on the sensitivity of the trade study. A single pair or multiple pairs of comparisons in the matrix were changed from the team's original prioritization shown in Table 2 for over 30 cases. Fluctuations in the AHP matrix that were consistent with the project's basic prioritization and kept acceptable consistency ratios, as described in Section III-B, resulted in ±5% deviation from the final reported survey scores in Table 8. In some cases, RCS outscored the FCS design but only by a fine margin. Meanwhile, in every case, MMCS remained significantly behind when the matrix was reasonably perturbed. Only a major shift in preferences, such as choosing packaging and stowage efficiency to be the highest-priority FOM, would result in a MMCS score that is equivalent to but never better than the survey scores of the other designs. However, no justification for changing preferences exists at this time, so FCS and RCS configurations emerged as the top control systems.

Between these two high-scoring designs, the team unanimously agreed to downselect to the FCS design because of its exceptional control system capability, offering the best maneuverability out of the three configurations. In contrast to RCS, the FCS design also demonstrated that it could command an instantaneous β, indicating that FCS offers added trim augmentation. The FCS design has major integration issues, but the team decided that these issues are worth resolving to further develop a design that promises remarkable performance and notable available payload volume.

The goal of the trade study was to downselect to a single G&C configuration to pursue in the next phase of the project. The approach described in this paper provided a transparent way for the team to gather results, openly discuss rationales, and confidently make a decision. Yet, the fact that added scrutiny was required after conducting the survey suggests that our trade study methodology could be improved. For instance, the project had a desire to keep track of cost and risk for each G&C design but including them in the trade study analysis was ultimately ineffective. Unlike the models used to inform performance and effectiveness FOMs, cost and risk models were low fidelity, and given the project's priorities at this phase, corresponding cost and risk FOMs had little impact on the weighted total scores. Instead, cost and risk FOMs diverted weight away from the more important FOMs. Removing these FOMs from the trade study has the effect of separating the G&C designs more effectively, resulting in weighted total scores of 82% for the FCS design, 42% for the MMCS design, and 72% for the RCS design, which is consistent with the team's downselect decision. Developing cost and risk models this early in the design phase had the advantage of setting the foundation for these models to be expanded and refined later but was not needed in the trade study. In retrospect, we learned to carefully consider the context of the design lifecycle stage to determine what truly needs to be included in any trade study.

V. Conclusion

This paper describes the methodology Pterodactyl followed to conduct a trade study of three novel G&C designs that can be integrated with a DEV. Analysis of FOMs, using AHP to convey FOM weights, creating and performing a trade study survey, and communicating trade study results enhanced the team's understanding and added rigor to the project's downselection. Trade study results demonstrated that FCS and RCS designs offer promising control system capability without negatively impacting mass. Therefore, they achieved the highest total weighted survey scores. Impressive performance and effectiveness of both designs come at the cost of compromised packaging and stowage efficiency, which poses future design challenges with regard to integration of both designs with DEVs. However, these risks are considered surmountable with further work. Ultimately, the FCS design was downselected as the most feedforward configuration for an LNA evaluated with bank control.

Acknowledgements

The authors gratefully acknowledge the support provided by NASA STMD's ECI program—particularly the program executive, Ricky Howard, and our project mentor and EDL Principal Technologist, Michelle Munk—for guiding and funding this work. The authors would also like to thank our independent review board chair, Alicia Dwyer Cianciolo, and review board members—Michelle Munk, Henry Cordova, and Zachary Putnam—who provided insightful observations and recommendations on our technical work and downselect process.

References

---

[1] Braun, Robert D., and Manning, Robert, M., "Mars Exploration Entry, Descent, and Landing Challenges," *Journal of Spacecraft and Rockets*, Vol. 44, No. 2, 2007, pp. 310-323.

[2] Price, Humphrey, Manning, M. Robert, Sklyanskiy, Evgeniy, and Braun, Robert D., "A High-Heritage Blunt-Body Entry, Descent, and Landing Concept for Human Mars Exploration", *AIAA SciTech 2016 Forum*, AIAA 2016-0219, San Diego, CA, 2016.

[3] Braun, Ibid.

[4] Jawin, Erica R., Valencia, Sarah N., Watkins, Ryan N., Crowell, James M., Neal, Clive R., & Schmidt, Gregory, "Lunar Science for Landed Missions Workshop Findings Report," *Earth and Space Science*, Vol. 6, No. 1, 2019, pp. 2-40.

[5] D'Souza, Sarah N., Okolo, Wendy A., Nikaido, Ben E., Yount, Bryan C., Tran, Jason, Margolis, Benjamin W.L., Smith, Brandon P., Cassell, Alan M., Johnson, Breanna J., Hibbard, Kenneth E., Barton, Jeffrey D., and Hays, Zane B., "Developing an Entry Guidance and Control Design Capability Using Flaps for the Lifting Nano-ADEPT," *AIAA Aviation 2019 Forum*, AIAA 2019-2901, Dallas, TX, 2019.

[6] Cassell, Alan M., Wercinski, Paul F., Smith, Brandon P., Yount, Bryan C., Ghassemieh, Shakib M., Nishioka, Owen S., Kruger, Carl E., Brivkalns, Chad A., Makino, Alberto, Wu, Shang C., Mai, Nghia N., McDaniel, Ryan D., Guarneros-Luna, Ali, Williams, Joseph D., Hoang, Dzung T., Rowan, Richard L., Dutta, Soumyo, Korzun, Ashley M., Green, Justin S., Tynis, Jake A., and Karlgaard, Chris, "ADEPT Sounding Rocket One Flight Test Overview," *AIAA Aviation 2019 Forum*, AIAA 2019-2896, Dallas, TX, 2019.

[7] NASA/Space Technology Mission Directorate, "Center Innovation Fund 2016 Winners Nano-ADEPT Lifting: Design Development for a Lifting Flight Test Demonstration," 2016. URL https://www.nasa.gov/centers/ames/cct/office/cif/p-wercinski.

[8] D'Souza, Ibid.

[9] Yount, Bryan C., Cassell, Alan M., and D'Souza, Sarah N., "Pterodactyl: Mechanical Designs for Integrated Control Design of a Mechanically Deployable Entry Vehicle," *AIAA SciTech 2020 Forum*, AIAA, Orlando, FL, 2020.

[10] Nikaido, Ben E., D'Souza, Sarah N., Hays, Zane B., and Reddish, Brandon J., "Pterodactyl: Aerodynamic and Aeroheating Database Development for Integrated Control Design of a Mechanically Deployable Entry Vehicle," *AIAA SciTech 2020 Forum*, AIAA, Orlando, FL, 2020.

[11] Johnson, Breanna J., Rocca-Bejar, Daniela, Lu, Ping, Nikaido, Ben E., Yount, Bryan C., D'Souza, Sarah N., Hays, Zane B., "Pterodactyl: Development and Performance of Guidance Algorithms for a Mechanically Deployable Entry Vehicle," *AIAA SciTech 2020 Forum*, AIAA, Orlando, FL, 2020.

[12] Okolo, Wendy A., Margolis, Benjamin W., D'Souza, Sarah N., and Barton, Jeffrey D., "Pterodactyl: Development and Comparison of Control Architectures for a Mechanically Deployable Entry Vehicle," *AIAA SciTech 2020 Forum*, AIAA, Orlando, FL, 2020.

[13] Hays, Zane B., Yount, Bryan C., Nikaido, Ben E., Tran, Jason, D'Souza, Sarah N., Kinney, David J., and McGuire, Mary K., "Pterodactyl: Thermal Protection System for Integrated Control Design of a Mechanically Deployable Entry Vehicle," *AIAA SciTech 2020 Forum*, AIAA, Orlando, FL, 2020.

---

[14] Yount, Ibid.
[15] Johnson, Ibid.
[16] Way, David W., Davis, Jody L., and Shidner, Jeremy D., "Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation," *AAS/AIAA Space Flight Mechanics 2013 Meeting*, AAS 13-420, Kauai, HI, 2013.
[17] Margolis, Benjamin W.L., Okolo, Wendy A., Nikaido, Ben E., Barton, Jeffrey D., and D'Souza, Sarah N., "Control and Simulation of a Deployable Entry Vehicle with Aerodynamic Control Surfaces," *AAS/AIAA Astrodynamics Specialist 2019 Conference*, AAS 19-919, Portland, ME, 2019.
[18] Okolo, Ibid.
[19] Saaty, Thomas L., *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, RWS Publications, Pittsburgh, 1982.
[20] Escobar, María T., Aguarón, Juan, and Moreno-Jiménez, José M., "A Note on AHP Group Consistency for the Row Geometric Mean Prioritization Procedure," *European Journal of Operational Research*, Vol. 153, No. 2, 2004, pp. 318-322.
[21] Venkatapathy, Ethiraj, and Glaze, Lori, "ADEPT-VITaL" NASA Mission Feasibility Report, 2013.
[22] Dwyer Cianciolo, Alicia M., Davis, Jody L., Komar, David R., Munk, Michelle M., Samareh, Jamshid A., Williams-Byrd, Julie A., and Zang, Thomas A., "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report," NASA TM-2010-216720, 2010.
[23] Moon, Yongjun, Jang, Tae Seong, Park, Chul, and Kwon, Sejin, "Requirements Analysis of Propulsion Systems for Lunar-Exploration Mission," *Journal of Spacecraft and Rockets*, Vol. 50, No. 3, pp. 620-631.
[24] Vaidya, Omkarprasad S., and Kumar, Sushil, "Analytic Hierarchy Process: An Overview of Applications," *European Journal of Operational Research*, Vol. 169, 2006, pp. 1-29.
[25] Ho, William, "Integrated Analytic Hierarchy Process and Its Applications – A Literature Review," *European Journal of Operational Research*, Vol. 186, 2008, pp. 211-228.
[26] Saaty, Thomas L., "Decision Making with the Analytic Hierarchy Process," *International Journal of Services Sciences*, Vol. 1, No. 1, 2008, pp. 83-98.
[27] Saaty, Ibid.
[28] Alonso, Jose A., and Lamata, María Teresa, "Consistency in the Analytic Hierarchy Process: A New Approach," *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, Vol. 14, No. 4, 2006, pp. 445-459.
[29] Johnson, Ibid.
[30] Yount, Ibid.
[31] Nikaido, Ibid.
[32] Johnson, Ibid.
[33] Okolo, Ibid.
[34] Hayes, Ibid.
[35] Johnson, Ibid.
[36] Okolo, Ibid.
[37] Yount, Ibid.
[38] Hayes, Ibid.
[39] Lopez, Gabriel, Wolfarth, Lawrence S., and D'Souza, Sarah N., "Pterodactyl: Cost and Risk Assessments for Integrated Control Design of a Mechanically Deployable Entry Vehicle," *International Planetary Probe Workshop*, IPPW, Monterey, CA, 2020.
[40] Lopez, Ibid.