Probabilistic Approach to Assessing CCRS Capture System Performance Margin

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In the aerospace industry, there are standard design principles and/or rule-of-thumb targets that define healthy levels of margins required at each developmental milestone for traditional metrics, such as mass, thermal, and power margins. When the technical resource is "non-traditional" in the sense that guiding margin principles are non-existent, systems engineering judgment is required to internally generate performance targets and methodologies to assess the system against the derived targets. This paper presents a probabilistic approach for assessing complex time-critical operations in order to apply global sensitivity analyses to identify input parameters that should (or should not) serve as design drivers.

I. Introduction

As part of the NASA Mars Sample Return (MSR) campaign to bring samples of Martian regolith back to Earth, the Capture, Containment, and Return System (CCRS)[1] payload on the Earth Return Orbiter (ERO) mission is responsible for a key capability for the campaign. The success of the ERO mission hinges on the ability of the CCRS system to capture the orbiting sample (OS) on the timescale of seconds. The CCRS project has a requirement that it *shall prevent the OS from exiting the capture volume after contact.* Although the requirement to capture the OS is not written in probabilistic terms, the verification thereof might require a probabilistic analysis approach. Not only is the CCRS assessment of its capture performance against this requirement dependent on several parameters outside its control, but the uncertainties in those parameters are broad and often ill-defined, especially in the preliminary design phases of the missions. Additionally, the problem becomes more complex to bound and assess when developmentally, the four entities are out-of-phase. Figure 1 summarizes the external entities and the parameters within their control that directly impact the ability for CCRS to capture the OS. Each of the parameters have their own probability distributions and confidence levels given where each project is in their developmental life cycle.

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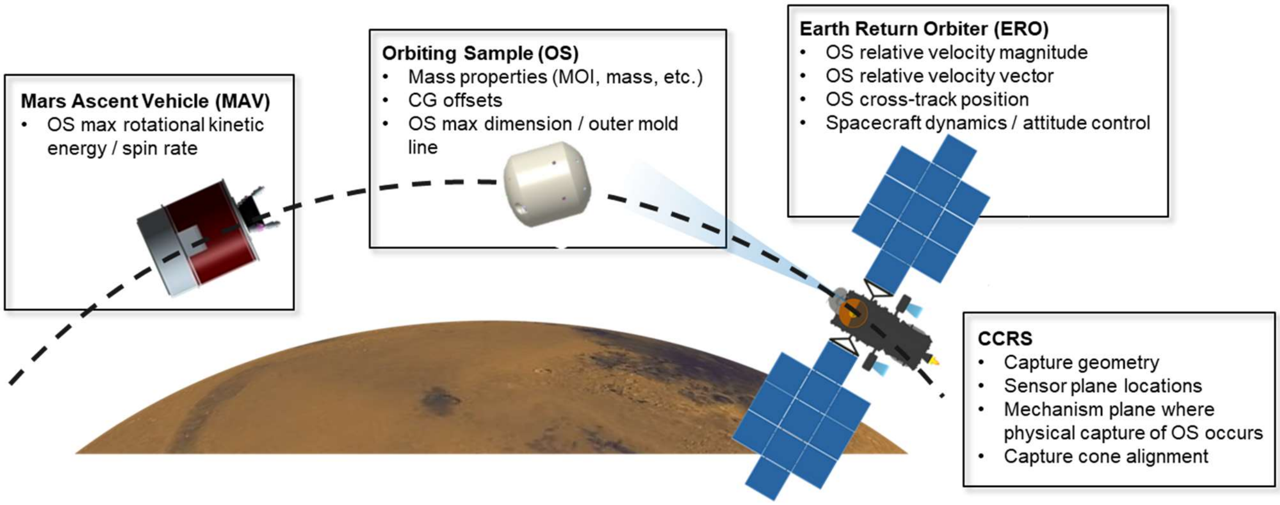

Figure 1. Input parameters to CCRS capture performance

In the early phases of a project when simplified assessments dominate as the means to derive working numbers for detailed design (i.e., hardware sizing), the computations are often conservative by nature. As designs mature and uncertainties are refined, the hope is that the design still stands, and it usually does. Other times, unknown unknowns are uncovered, and the design changes required to accommodate the unknowns come at the expense of both technical resource constraints (i.e., mass, volume, etc.), and programmatic constraints (i.e., schedule, cost, etc.). When all the input parameters are stacked at their worst-case requirement bounds, which typically provides the first-order approximation that may be used in early design phases, it not only misrepresents the true distributions (and uncertainties) for each parameter, but it also produces an overly conservative result that may unnecessarily drive a mass-constrained system.

Adopting a stochastic (e.g., Monte Carlo) approach, therefore, to understand what input parameters ought to drive design changes in a highly constrained system becomes necessary in order to balance risk across all entities. This paper applies common probabilistic methods in order to define sufficient levels of margin, or system robustness, for time-based estimates of highly coupled relative dynamic problems. Margin for traditional technical resources, such as mass and power, are generally expressed in percent (i.e., 20% mass margin at preliminary design review). Rather than reporting metrics for CCRS' time-critical capture performance margins in terms of an absolute percentage of seconds, which provides very little indication on system robustness, this paper aims to: (1) report performance as the probability that the defined system capability limit will successfully execute and meet its capture requirement, and (2) apply a widely used global sensitivity analysis methodology and risk assessment to express capture margin as a sigma value to its most sensitive input parameter.

II. Overview of CCRS Capture Performance Definition

The CCRS has a dedicated capture volume to receive the OS during rendezvous, consisting of a cylindrical portion and a funnel portion. CCRS is blind to the exact time the OS enters the aperture of the capture volume and, thus, has implemented two LED layers (called capture sensors) to detect the presence of the OS. The on-board CCRS avionics process the signals from the capture sensors to determine when the system should deploy a mechanism to capture the OS. The avionics implements the following high-level algorithm: obstruction of the upper LED layer → obstruction of upper + lower LED layers → un-obstruction of upper LED layer + obstruction of lower LED layer. Once the OS has traversed below the upper capture sensor layer, it has cleared the plane of the mechanism used to physically trap the OS in the capture volume and, therefore, this is the start of the capture timing budget, also designated as the "trigger time" for capture.

After the trigger time, the OS then continues into the capture volume, contacts a (random) point within the CCRS capture volume and bounces back towards the capture aperture to the plane of the mechanism used to capture the OS, called the Linear Transfer Mechanism (LTM). It is at the point when the OS bounces back to the plane of the LTM that the capture timing budget ends. The entire budget from trigger time until this ending point is termed the total capture-before-bounce-back budget, against which the CCRS system must perform to meet its functional requirement to prevent the OS from leaving the capture volume.

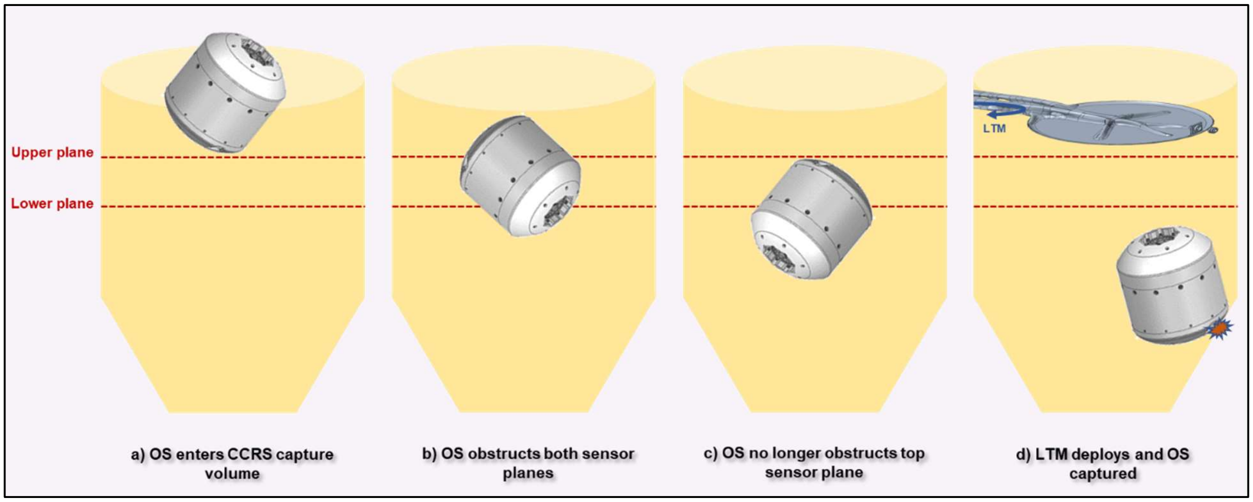

Figure 2. Capture Storyboard

Once capture is triggered (Figure 2c), the CCRS system has three hardware components that execute the closed-loop capture function within the capture-before-bounce-back budget. Table 1 provides the hardware component allocations, including a list of any uncertainties that are expected to be covered within the not-to-exceed (NTE) allocations for each subsystem.

Table 1. Capture-Before-Bounce-Back Timing Allocation

Item	Hardware Item	NTE Timing Allocation (s)	Description and Uncertainties
1	Capture sensor electronics	0.125	• CSE processing for state determination. • Design changes (i.e. trade space for beam brake sensor locations, LTM pocket depth) thru CDR
2	LTM WHA swing arm	2.325	• Deploy LTM • Uncertainties: temperature, WHA input voltage, WHA torque/speed output, hinge resistive torques (i.e. lube viscosity), swung inertia maturity
3	Avionics (FPGA, Harness, Power)	0.45	• Receive capture sensor statuses • Algorithms including persistence • Send command to mechanism
	CCRS System Total	**2.9**	**System capability limit**

Margins for the capture before-bounce-back timing are held at the subsystem, CCRS system, and ERO-CCRS/Sample Retrieval Lander (SRL)-CCRS missions-levels:

- Subsystem allocations are NTE values that are meant to absorb uncertainties in the design and subsystem performance. These NTEs are reflected in Table 1 and are used to set the system capability limit.
- CCRS system margin absorbs any internal design changes that would impact capture timing (i.e., capture volume changes, captures sensor plane locations, LTM plane, etc.) outside the performance capability of each hardware component (which is covered in the previous bullet).
- Interface requirements between two systems inherently have margin. For instance, the ERO controls the incoming OS rendezvous parameters (OS relative velocity magnitude, velocity vector, and lateral offset), which are governed in requirements space; there is margin held against these requirements, and since they are inputs to the capture margins, an understanding of the margins held across an interface becomes essential should CCRS system margins become insufficient, and negotiations ensue.

III. Applying the General Monte Carlo Process

A. Parameters and Distributions
In order to determine performance margins of the capture system, distributions for external parameters must be factored into the analysis and, thus, CCRS applies a Monte Carlo (MC) simulation[3] to identify probabilistic metrics for assessing end-to-end capture performance. The MC capture simulations are performed with commercial Multi-Body Dynamics analysis software, ADAMS, starting when the OS is at the entrance plane (rendezvous) and ending after many impacts when the OS kinetic energy has dissipated. This model includes a component mode synthesis model of the CCRS capture volume geometry to accurately represent the local compliance and a rigid OS. Table 2 summarizes the randomized parameters and their respective distributions. The primary outputs of interest from the MC simulation are: (a) the time of OS first impact; (b) the location of OS first contact; (c) the number of capture successes vs. failures. Failures are defined in two possible cases: (1) the OS does not make it into the capture volume, and (2) the OS bounces out before the system is able to deploy the LTM to physically cage it.

Total capture-before-bounce-back budget = time-until-contact from MC + bounce-back time computed as a fully elastic contact

Table 2. Monte Carlo Input Parameters and Distributions

#	Capture-before-bounce-back Input Parameter	Value [Reqt*]	Input Distribution for Monte Carlo Budget Derivation
System			
1	OS Velocity (cm/s)	≤4 cm/s*	Fixed
2	OS Cross Track (cm)	≤10*	Gaussian distribution with 3 sigma at reqt values
3	OS Trajectory Angle (deg)	≤5*	Uniform distribution +/- 5 deg
4	OS Max Dimension (mm)	254*	Assumes CG at centroid
5	OS CG Offset (mm)	±10 X_{OS}; ±5 radial*	Uniform CG, Uniform Offset
6	OS Max Rotational KE (J)	0.35*	Uniform distribution from 0-0.35J
7	OS MOI (kg-m^2)	See reqt	Uniform
8	S/C dynamics	±0.025 deg/s	Uniform
9	OS Intial Orientation	[0 360 deg] 3 Eugler angles	Uniform
Time Before Contact, from OS Cleared Upper Sensor Plane		5.05	Not a gaussian distribution, nonlinear model (TBC)
Factors w Estimated Values (Not Represented in Monte Carlo)			
10	Additional bounce-back time (sec)	0.78	N/A
11	Capture volume mis-alignment wrt capt axis	-0.1 sec (TBR)	

B. Key Input Parameters
A global sensitivity analysis[4] using the primary outputs of the MC was used to identify the main drivers in the form of Sobol' main indices. The Sobol' main index measures the fraction of the total output variance that can be attributed to an input alone, whereas the total index measures the fraction of the total output variance that can be attributed to an input as well as its interactions with other inputs. Inputs with larger sensitivity indices contribute more to output uncertainty. Computing Sobol' indices for all inputs thus allows inputs to be ranked in terms of importance, enabling engineers to drop unimportant inputs for simplified analyses or to prioritize further characterization of important inputs to reduce the overall output uncertainty. Here, the Gamboa approach[5,6] was employed to compute the 17 Sobol' main indices and identify the OS cross-track error as the dominating parameter to which the capture timing is most sensitive with a Sobol' main index of 0.3. Sizing the opening diameter for the capture volume, therefore, uses the OS cross-track error as the design-to parameter; traditionally, a 3-sigma value is considered a sufficient design point, but the CCRS capture cone has been designed to the 3.8-sigma on the cross-track error. In terms of the sizing of the capture volume length, the OS velocity and OS trajectory angle are the parameters to which that dimension is designed.

C. Derived Performance Targets
To set capture performance targets, engineering judgment must be used when there are no established guiding principles for the technical resource. The two driving factors that were considered in setting the performance metrics for CCRS capture and their associated targets are: (1) the uncertainties and threats to the performance, with extra emphasis on the parameters to which the system is most sensitive and (2) the level of acceptable risk with which the stakeholders are comfortable in a mission-critical, time-critical, operation. In consideration of these factors, the following capture performance metrics and targets were set for the system:

Table 3. Capture Performance Metrics and Targets

Metric	Target	Comments
Percent System Margin for Capture Timing	0.15% total capture-before-bounce-back has the following margins: • 20% at Preliminary Design Review (PDR) • 15% at Critical Design Review (CDR) • 10% at Payload Delivery	Margin (in percent) = (Available Resource-Estimated Value of Resource)/Available Resource X 100 • Available resource = 0.15% first impact time • Estimated value of resource = system capability
Probability of successful capture	≥99.9% success for 5,000 capture attempts	Stakeholder / customer specification

IV. Results

Preliminary MC results based on the randomized parameters in accordance to the distributions indicated in Table 2 suggest that there is sufficient capture performance margins with respect to the timing target specified in Table 3. The preliminary results also imply that the probability of success is not quite sufficient to meet the target probability. Figure 3 provides the 5,000-case MC histograms representing (a) the time of first impact with respect to the trigger time; (b) the location of first impact; (c) the associated impact distance along the length of the cone; (d) the bounce-back time; and finally (e) total capture-before-bounce-back time. The bounce-back time represented in Figure 3d was computed for each MC-case as follows:

- At instant of 1st impact record clearance between trailing edge of OS (closest to capture plane) and LTM, D_ltm
- Compute max possible translational velocity assuming no energy loss and initial KE: Vt_max = sqrt(KE*2/mass)
- Bounce-back time = D_ltm/Vt_max, assumes all incoming kinetic energy converted to translation and rebounds directly along capture cone longitudinal axis

The total capture-before-bounce-back time Figure 3e is simply the addition of the time before trigger (Figure 3a) and bounce-back time (Figure 3d).

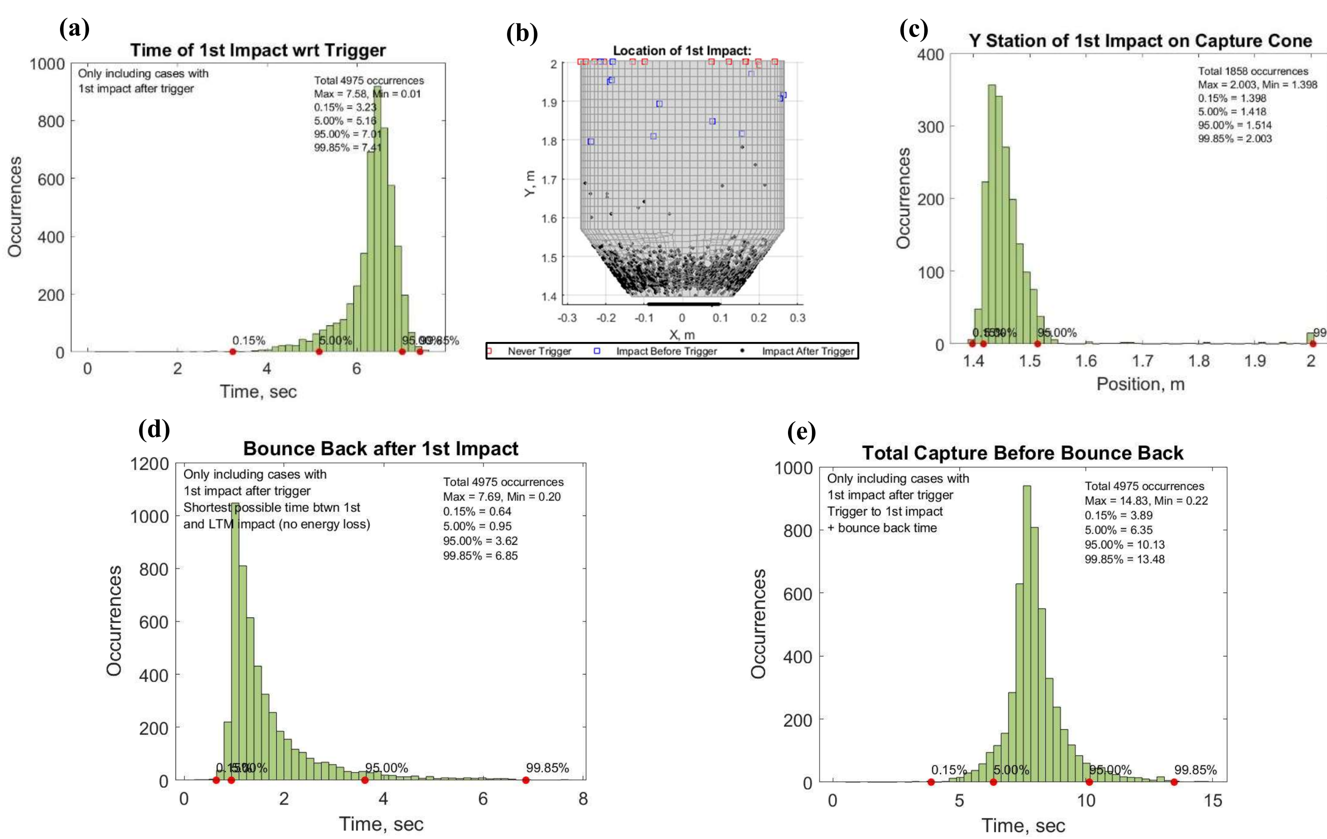

Table 4. Capture Performance Results

Metric	Current Performance	Current Delta from Target	Details
Percent System Margin Capture for Timing	25.5% margin	+5.5%	• 0.15% from Figure3e = 3.89sec
Probability of successful capture	99.7% success	-0.2%	• 13 failures (out of 5,000) = 4987 successes

V. Conclusion

When the performance assessment of a technical parameter is complex and highly dependent on dynamic external interfaces, it is crucial to understand and properly represent the probability distributions for the inputs when ingesting them into the computations. This paper demonstrates a probabilistic approach using MC to assess the CCRS capture performance against self-derived targets. Similar thought processes can be applied to other non-traditional technical resources where performance targets are non-existent in the industry.

In the preliminary assessment represented in this paper, each input parameter for the MC has conservatism baked into it, so any additional simplifying assumptions used to compute the capture-before-bounce-back time adds further margin that is not seen at the system-level. For instance, this study assumes that all rotational kinetic energy is converted to translational kinetic energy at first contact for all MC cases, which has some clear conservatism and built-in margin, and that the OS rebound velocity vector is in the worst-possible direction. The current target values for each metric, therefore, includes more margin than readily apparent. Future work, therefore, should consider refining and possibly reducing the target value for each performance metric identified to account for existing conservatism..

VI. References

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