

# Feasibility of the SIMAC for the NASA Docking System

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**In April 2012, NASA directed Boeing to conduct a study to assess the feasibility of implementing a simplified soft capture system, as a possible replacement for the soft capture system portion of the baseline NASA Docking System (NDS). This paper describes the study conducted and conclusions drawn that supported the selection of the Soft Impact Mating and Attenuation Concept (SIMAC) as the replacement of the International Low Impact Docking System's (iLIDS) soft capture system.**

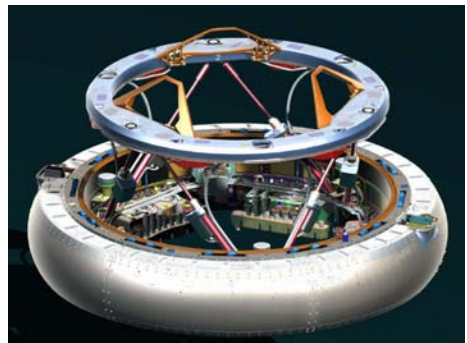
## I. Introduction

**A**PRIL 2012, NASA International Space Station (ISS) Program management initiated a Change Directive to Boeing that authorized and funded a study to determine if a less complex docking system could be implemented for use as the NASA Docking System that both met the international community's desire for a narrow soft capture system ring width, as well as providing the ISS a simpler active docking system compared to the then-current iLIDS design, shown in Figure 1. Any proposed concept was to be developed to a level of maturity that would enable NASA to determine technical and schedule risks associated with the alternate approach.

The purpose of the NDS is to provide the means by which two spacecraft can establish a pressurized, man-rated physical connection for the passage of people and resources between two spacecraft. The three major subsystems of the NDS include a Soft Capture System (SCS), a Hard Capture System (HCS) and a Docking System Controller (DSC). The DSC coordinates the functions of the SCS and the HCS. The SCS performs the initial capture, alignment and retraction of the two spacecrafts towards each other, as the chasing vehicle is purposefully guided towards the stationary target spacecraft. When the SCS has completed its function and has drawn together the two spacecraft, the HCS creates the final, rigidized connection that supports pressurization of the connection and the typical structural loads from on-orbit guidance, navigation and control of the mated vehicles.

While the focus of NASA's Change Directive was clearly on an alternate for the soft capture system portion of the entire docking system, the overall goal was to create a complete, integrated system that worked well together. NASA's guidance and direction for the study included a number of requirements and goals, listed below:

- The Soft Capture System (SCS) shall be compatible with a passive or active Androgynous Peripheral Attachment System (APAS) style SCS
- Hard mate assembly/hard capture system shall be per the International Docking System Standard IDSS Interface Definition Document (IDSS IDD)
- Use of Technology Readiness Level 6 or higher technologies is required
- Design, development, qualification and certification of a final design is required to be completed by June 2015
- The design shall contain no proprietary features
- Loads are as documented in IDSS Interface IDD Revision A
- The design shall be as simple and robust as possible
- The design shall allow build-to-print capability by third parties (must use publically available process and data)



**Figure 1. iLIDS Docking System shown with active soft capture ring extended**

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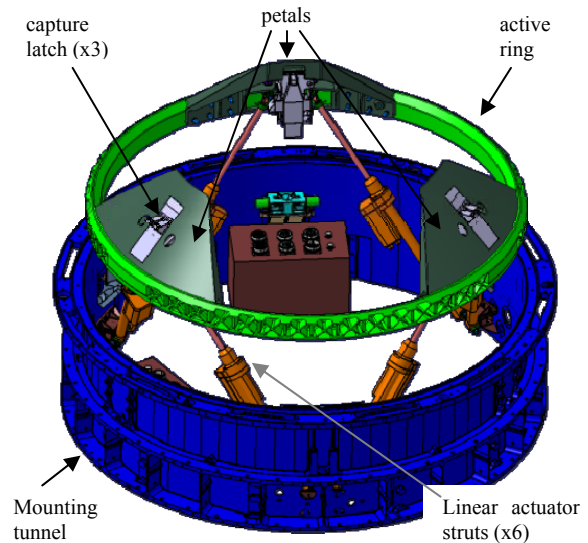
Boeing narrowed its focus to two potential concepts from several possibilities, one of which was the SIMAC. More detailed studies were then conducted to explore predicted performance of the two concepts, as well as compare the relative maturity, development path, degree of compliance to the NASA requirements, and remaining risk.

## II. Overview of the Soft Impact Mating and Attenuation Concept

Originally conceived in 2003 under a NASA contract in support of the Orbital Space Plane (OSP) Program, the SIMAC consists of six linear actuators connecting a vehicle-mounted tunnel to soft capture ring in a Stewart platform arrangement, as shown in Figure 2. The linear actuators position and move the soft capture ring in a fashion to force alignment of the active ring to the passive ring, in the presence of reasonable initial relative misalignments and rates between the two rings, so that capture devices on the rings can trap the two rings together for a successful soft capture. Subsequently, the active ring halts remaining relative vehicle motion, aligns the passive half to the chasing vehicle tunnel at an appropriate standoff distance, and then retracts the passive half to fit against the active half tunnel in preparation for the HCS to rigidly dock the vehicles together.

A central feature of the SIMAC is the independence of each of the six linear actuators from each other, without the need of either mechanical interconnection between the actuators or complicated closed loop control between them. All actuators are simultaneously commanded to operate in succession of operational modes, and in each mode, each actuator operates independently to effect the goals of that mode. Another important characteristic is the load-limiting nature of each linear actuator. While in a particular operational mode, each linear actuator independently limits the load applied by it, as specified for that particular mode. This last characteristic limits the total load applied by the soft capture ring to the passive ring and structure behind it. With appropriate implementation, the individual actuator load limits can be varied on-orbit, providing flexibility to accommodate a wider range of vehicle masses.

The independence of the actuators reduces the amount of hardware in the form of interconnectivity as well as sensors, thus reducing weight, and consequently reducing complexity and risk while increasing reliability of the system as a whole.



**Figure 2. Major Components of the SIMAC: APAS compatible narrow ring (green) and petals; 6 passive, linear actuator struts (light brown)**

## III. SIMAC Performance Details

### A. Summary of Operational Modes

In order for a chaser vehicle to utilize SIMAC to dock with another spacecraft, a sequence of operational modes should be executed, with the linear actuators behaving in a specific manner in each mode. This sequence includes deployment from a “stowed” configuration of the active soft capture ring to a “ready for capture”, extended state; execution of a “lunge” maneuver of the soft capture ring to effect alignment and capture of the passive capture ring; transitioning to an “attenuate” mode to remove remaining relative motion, executing an “align” mode to align the active and passive rings, concluded by a “retract” mode to bring the vehicles together in preparation for a rigidized physical connection, or hardmate. While the sequence can be manually commanded mode-by-mode, certain mode changes can be time-critical, such as initiation of the attenuation mode, thus motivating an instrumented identification of successful capture, triggering a transition to the attenuate mode.

### B. Actuator Performance Requirements for Critical Operational Modes

Each operational mode of SIMAC requires specific actuator performance requirements in order to successfully accomplish the purpose of the mode. The characteristics of the most important modes will be briefly discussed below.

### 1. Lunge Mode

The Lunge mode extends the active soft capture ring in order to effect alignment with and capture of the passive capture ring. In order for this to be accomplished successfully, the six linear actuators are simultaneously commanded to extend at a specified rate as soon as contact is detected between the active and passive soft capture rings. Once commanded, the behavior of each linear actuator is independent of the others, and continues until capture is achieved. Stroke and time limitations can also be imposed on how long the actuators remain in lunge mode.

The geometry of the active and passive soft capture rings and associated petals, assumed to be similar to that of the Russian APAS, forces physical alignment and subsequent capture when the rings are axially pushed towards each other. For this to occur, the six linear actuators' extensions cannot be purely kinematic; rather, some linear actuators must extend to a longer length than others in order to be able to push the active soft capture ring into a relative linear and angular position that matches the passive soft capture ring. To accomplish this, each linear actuator's extension rate is inversely proportional to the resistance encountered while trying to extend. As a linear actuator encounters resistance, its extension rate is slowed from the commanded, or "no-load", extension rate. There is also a limit to the maximum force a linear actuator will apply during this extension, which is an important feature to prevent the active ring from pushing away the passive ring before capture takes place. In fact, if a particular linear actuator is pushed at this maximum force level, it can be forced to retract or "slip" while other linear actuators are still extending. This behavior is central to this mode's goal of forcing alignment and capture.

Parameters of this mode of operation include the actuator's no-load lunge rate, the maximum or "slip" force level and the relationship between the resistance encountered and the extension rate. Figure 3 depicts a particular way an actuator could behave in this lunge mode.

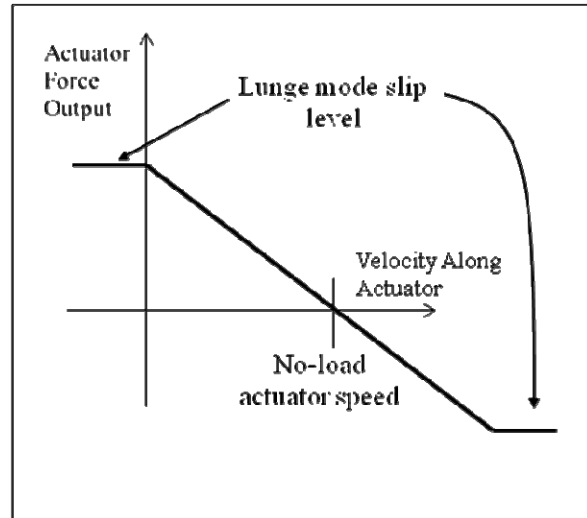


Figure 3. Lunge mode actuator behavior

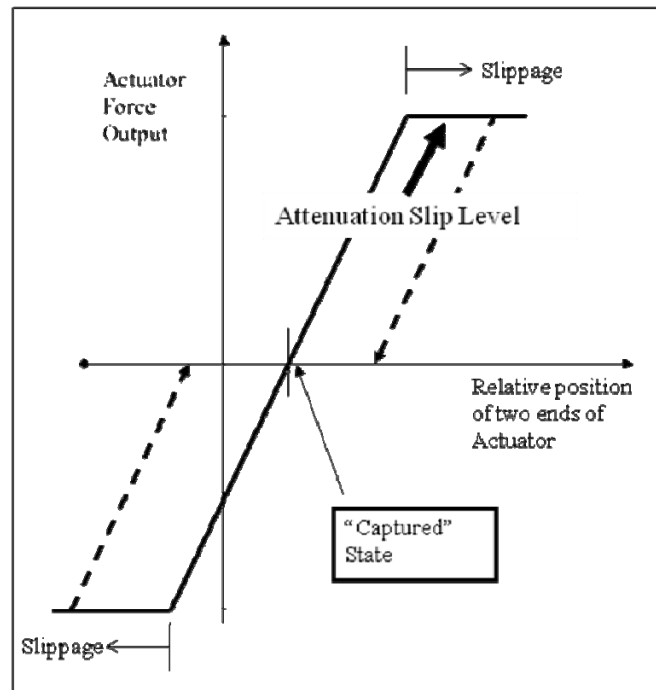


Figure 4. Attenuate mode actuator behavior

### 2. Attenuate Mode

Entry into the attenuate mode is typically triggered by successful capture of the passive ring by the active ring during the lunge mode. At this point in time, there still remains relative motion between the chasing and target vehicles, and the objective is to bring all relative motion to a halt.

The SIMAC accomplishes this by commanding each linear actuator to halt commanded extension and instead, maintain its latest sensed position, while simultaneously limiting the force applied.

Thus, if a particular linear actuator is pushed harder than the maximum specified slip force level of the attenuate mode, that actuator simply "slips" from its currently memorized position while resisting with the maximum slip force, much like a slip clutch. In this way, the maximum amount of energy absorption is afforded at the linear actuator level while the load is also limited to a specified level in order limit the overall active↔passive ring interface loads. The parameters of this mode include the maximum slip level as well as the stiffness and damping

characteristics of the linear actuator while within the limits of the maximum slip level. Figure 4 depicts the behavior of a linear actuator in the attenuate mode.

There could be several different ways of implementing this behavior, including mechanical friction, magnetic-damping and fluid-damping slip clutches, as well as electro-mechanically programmed and controlled actuators.

### 3. Align & Retract Modes

The align mode commands the actuators to extend or retract to a predetermined length, resulting in the alignment of the soft capture ring, and thus the captive passive capture ring, with the tunnel. This mode prepares for bringing the passive capture ring to the tunnel interface so the HCS can establish a rigid connection between the two vehicles. Depending on the kind of linear actuator implementation, the align mode can command each actuator to extend to its hard stops at full extension, or some other convenient length.

The retract mode commands the actuators to simultaneously retract from the end of the aligned mode state, to a length that brings the hard capture system halves on the active and passive sides close enough for them to establish a rigidized structural connection. This operation requires a sufficiently synchronized and accurate motion of each actuator such that the active ring's position and orientation relative to the tunnel is within required tolerances for the hard capture system to perform its function. Thus, there will be some required position accuracy requirement imposed on the actuators, particularly for retraction.

In both the retraction and alignment modes, there is still a desire to limit the interface loads during actuator motion. Thus, the actuator acceleration and speed during these two operations, is constrained by maximum load limits. In a fashion similar to the maximum slip level of attenuate mode, these two modes also allow the actuator to slip if a specified load limit is reached.

## IV. Studies Conducted with the SIMAC

In support of the NASA Change Directive to identify, mature and recommend alternative soft capture system designs, the original OSP program's multi-body dynamics model of the SIMAC was leveraged to execute additional modeling and simulation work studying the predicted performance under new, NASA-specified conditions. To conduct this work, the original OSP program model of the SIMAC, constructed in the DADS multi-body dynamics commercial software, was ported into the ADAMS multi-body dynamics commercial software environment.

Several studies were undertaken to explore the performance of the SIMAC under the new NASA constraints and requirements.

### A. Study Constraints, Design Parameters & Performance Metrics

There are numerous parameters that serve as constraints, inputs, design parameters or performance metrics in the formulation of this study. Some were provided by NASA documentation, others are part of the design parameters of the SIMAC and some come from system-level constraints

#### 1. Relative Vehicle Initial Conditions, Interface Load Limits, Vehicle Masses

The IDSS IDD served as a key defining document for many of the study constraints and inputs, including the interface loads, the relative vehicle initial conditions and the vehicle masses. Per the IDSS IDD, these three sets of parameters were generated to be consistent with one another, but only the interface loads are specified as a requirement. The other two are described as *recommended*, in order to increase the probability of successful capture in all intended use cases. In our study, these other two are also treated as constraints.

The IDSS IDD specifies limits on the interface loads between the active capture ring and passive capture ring, shown in Table 1. Resulting loads predicted by simulation cases are checked against these limits to determine whether the SIMAC model parameters

Load	Limiting Value
Tension	3900 N
Compression (Static)	3500 N
Compression (Dynamic, up to 0.1sec)	6500 N
Shear	3200 N
Bending	2800 N*m
Torsion	1500 N*m

#### Notes:

1. Values are design limit loads.
2. Values are defined at the center of the SCS mating plane (see IDSS IDD)
3. Values are  $3\sigma$  maxima and shall apply simultaneously, not to exceed the component values (see IDSS IDD)
4. Shear loads may be applied in any direction in the SCS mating plane.
5. Bending moment may be applied about any axis in the SCS mating plane.

**Table 1. IDSS IDD definition of SCS maximum interface loads.**

need to be adjusted in some way to either reduce loads, or to trade excessive load margin for a change in performance in some other area, such as reduced actuator stroke or increased lunge rate.

The position and orientation of the active capture ring, as well as linear and angular rate, relative to the passive capture ring: these are collectively called the relative vehicle initial conditions (ICs). Table 2, taken from the International Docking System Standard Interface Definition Document (IDSS IDD), shows the description of limitations on the initial conditions that a docking system will have to operate successful under. Simulation studies used both a Monte Carlo set of 100 ICs using a normal distribution for these variables, as well as a hand-selected set of ICs at the boundaries of Table 2.

Another similar, but distinct guideline considered as part of this study was the NASA Docking System Interface Definition Document set of initial conditions, shown in Table 3. The NDS IDD limits were considered near the end of the study, to specify another set of hand-selected, worst-case ICs for evaluation. These relative vehicle ICs are one group of inputs needed to run a specific simulation case.

The IDSS IDD recommends a range of vehicle mass properties with which the docking system should successfully operate, shown in Table 4. Two pairs of mass properties were chosen for this study, in order to bound the performance extremes: a 5 metric ton (5T) chaser docking to another 5T vehicle, called “light⇌light”; a 25T chaser docking to a 350T target, called “heavy⇌heavy”. The light⇌light configuration provides the most difficult

condition for achieving a successful capture, since light vehicles will more easily push away from each other. The heavy⇌heavy configuration will definitely provide the maximum loads from slipping of the linear actuators and result in the most slipping in the lunge and attenuate modes.

Initial Condition	Limiting Value
Closing (axial) rate	0.05 to 0.10 m/sec
Lateral (radial) rate	0.04 m/sec
Pitch/Yaw rate	0.15 deg/sec (vector sum of pitch/yaw rate)
Roll rate	0.40 deg/sec
Lateral (radial) misalignment	0.11 m
Pitch/Yaw misalignment	5.0 deg (vector sum of pitch/yaw)
Notes:	
<ol style="list-style-type: none"> <li>1. Values are 3<math>\sigma</math> maxima and shall apply simultaneously in a statistically appropriate manner, provided that the reach capability of the internal petals is not exceeded.</li> <li>2. Closing (axial) rate may be increased to achieve necessary capture performance.</li> <li>3. Post contact thrust may be used to achieve necessary capture performance.</li> <li>4. Lateral (radial) rate limit includes combined lateral and rotational rates of both vehicles.</li> <li>5. Lateral misalignment is defined as the minimum distance between the center of the active soft capture ring and the longitudinal axis of the passive soft capture ring at the moment of first contact between the guide petals.</li> </ol>	

**Table 2. IDSS IDD definition of the relative vehicle initial condition limits.**

Initial Conditions	Limiting Value
Closing (axial) rate	Varies with vehicle mass combinations <sup>(3)</sup>
Lateral (radial) rate	0.15 ft/sec <sup>(4)</sup> (0.045 m/s)
Angular rate	0.15 deg/sec about NDS X axis; vector sum of 0.15 deg/sec about NDS Y and Z axes
Lateral (radial) misalignment	4.2 in. [106 mm]
Angular misalignment	4.0 degrees about NDS X axis; vector sum of 4.0 degrees about NDS Y and Z axes

Notes:

1. Initial conditions to be applied simultaneously.
2. The NDS will use a right-hand orthogonal body coordinate system, the origin of which lies in the intersection of the NDS cylindrical center line X-axis and HCS mating plane
3. Refer to the JSC-63844, NDS Capture Performance Data Book for applicable vehicle masses for these initial conditions.
4. Lateral (radial) rate limit includes combined lateral and rotational rates of both vehicles.
5. In order to achieve capture with these initial conditions, it may be necessary for Post Contact Thrust (PCT) firing with properties as defined in the JSC-63844, NDS Capture Performance Data Book.

**Table 3. NDS IDD definition of the relative vehicle initial condition “Design-To” limits**

Article	Mass (kg)	Moment of Inertia (kg*m <sup>2</sup> )						Coordinates of Ring Center (m)		
		Ixx	Iyy	Izz	Ixy	Ixz	Iyz	X	Y	Z
IDSS-350T	3.50E+5	1.15E+8	6.20E+7	1.65E+8	-2.30E+6	5.00E+5	4.60E+5	-20.0	0	2
IDSS-25T	25000	70000	169000	169000	0	0	0	5.4	0	0
IDSS-20T	20000	55000	135000	135000	0	0	0	4.3	0	0
IDSS-15T	15000	41000	71000	71000	0	0	0	4.1	0	0
IDSS-10T	10000	17000	42000	42000	0	0	0	3.5	0	0
IDSS-5T	5000	3400	18000	18000	0	0	0	2.3	0	0
Notes: 1. Moments of inertia (MOI) are about C.G. and products of inertia (POI) are positive integral. 2. Mass properties defined in coordinate system located at C.G. with X-axis along vehicle longitudinal axis and positive toward the docking interface.										

**Table 4. IDSS IDD-recommended vehicle mass properties consistent with ICs and Interface Loads**

## 2. Design Parameters

There are a group of design parameters associated with the SIMAC that were either carefully specified or varied as part of the study. These include capture latch resistance, actuator lunge rate, vehicle approach rate, ready-to-capture height, lunge mode slip level, attenuate mode slip level and actuator stroke limit.

The capture latch resistance is a momentary resisting force between the active and passive rings as they become aligned and the axial distance approaches the *captured* configuration. Historically it has been present in many docking systems which have a mechanical latching design where a latch must be physically displaced over a trapping striker plate. This resistance, though not large, can significantly impact the percentage of cases that successfully capture, since any additional resistance to the rings reaching full alignment can prevent them from reaching the captured state. While the iLIDS design utilized three magnetic capture plates and electromagnets to keep the rings together at capture, the final, desired method to be utilized by NASA was unclear at the time. Thus, direction was provided to assume the maximum APAS capture latch resistance, to be on the conservative side. The APAS uses three capture latch assemblies, one on each of the active soft capture ring's petals that clasp and trap the passive capture ring when the two rings are fully aligned and pressed against each other. The typically installed location of the APAS capture latches can be seen on 2 of the 3 petals of Figure 2. The resistance of these 3 capture latches was not varied in the study.

The vehicle approach rate describes how fast the vehicle with the active side of the SIMAC is approaching the passive vehicle. Table 2 provides limits for this parameter, but the vehicle actually approaches with some nominal approach rate, with some error that is normally distributed and within the limits. Thus, this was one parameter that our study treated as adjustable.

The "ready-to-capture" height, which is the starting height of the active soft capture ring, relative to the Stowed condition, was also treated as a design parameter that was varied to assist in meeting performance metrics and objectives. This parameter has the most significant impact on the maximum actuator stroke required in the process of achieving a successful capture.

The three critical SIMAC parameters varied in this study were the actuator lunge rate, the lunge mode slip level and the attenuate mode slip level. The actuator lunge rate dictates the rate at which the soft capture ring extends outward towards the target passive capture ring and petals. The lunge mode slip level determines the interface forces during lunge as well as the ability of the active ring to comply and effect a successful capture, in concert with the assumed actuator lunge rate. The attenuate mode slip level determines the maximum interface loads during the attenuation phase of docking, while also influencing the total actuator stroke due to the absorption of remaining energy from vehicle relative motion after a successful capture. The ranges for these three parameters were guided by feedback obtained from discussions with potential actuator vendors as part of this study's effort.

## 3. Performance Metrics

The actuator stroke limit, while not firmly specified during the study, was estimated from very preliminary system design and sizing efforts, considering both the space available in the installed conditions, as well as feedback from actuator vendors. Rather than modeling an actuator stroke limit, the SIMAC modeling and simulation analyses

simply made predictions of the maximum actuator strokes required, which were then compared to this estimated design maximum as a performance metric, rather than as a design parameter. The goal of the study was to predict maximum strokes below the estimated maximum limit.

While there was no requirement defined for Capture success, it is naturally one of the most important performance metrics. The goal was to predict a successful capture in 100% of cases simulated that started with ICs within the limits defined of Table 2. Thus, while not unacceptable to have some capture failure cases, any design adjustments to eliminate the capture failures were explored and implemented.

Keeping predicted interface loads below the limits defined in Table 1 is another central performance objective that guided design parameter adjustments.

## B. Study Simulations and Results

Simulations of the SIMAC concept were executed using a combination of MSC ADAMS, a commercial, off the shelf, multi-body dynamics modeling and simulation software, combined with unique Boeing FORTRAN code stemming from heritage Orbiter Docking System program as well as the Orbital Space Plane program. Contact representation of the active and passive rings and petals used test and flight-correlated code, while linear actuator modeling utilized code developed later, under the OSP program.

Preliminary simulations were executed assuming no Post-Contact Thrusting (PCT). PCT has been conventionally used by the Space Shuttle to significantly increase the probability of a successful capture. This is accomplished by firing thrusters, when initial contact is imminent, to accelerate the chaser vehicle towards the target to more definitively force together the active and passive capture rings of the APAS docking system. Table 2 from the IDSS IDD clearly permits such a procedure; however, acceptable performance without it would simplify the docking procedures and further reduce the docking loads.

Sequential cycles of analyses were conducted during this study, with each cycle involving further refinement of the design and input parameters. Each analysis cycle looked at performance for both light↔light and heavy↔heavy vehicles pairings. Table 5 briefly summarizes the important characteristics of the analysis cycles.

Analysis Cycle	ICs	Focus of Cycle	Lunge Slip Level	Attenuate Slip Level	Lunge Rate	Approach Rates Considered
1	1 <sup>st</sup> Hand-Selected Set of 18	Establish Performance Baseline	10 lbs	40 lbs	3 in/s	0.75 – 10 cm/s
2	1 <sup>st</sup> Hand-Selected Set of 18	Sensitivity Study on Slip Levels & Lunge Rate	15 lbs	80 lbs	4 in/s	0.75 – 10 cm/s
3	100 Random ICs, normally distribution	Prove robustness of Performance	15 lbs	80 lbs	4 in/s	1.5-4.5 cm/s
4	2 <sup>nd</sup> Hand-Selected Set of 17	Explore Performance Under Worst Case Conditions	15 lbs	80 lbs	4 in/s	1.5-4.5 cm/s & 4.5 – 7.5 cm/s

**Table 5: Summary of SIMAC study analysis cycles, listing key characteristics of each.**

### 1. Initial Analysis

The goal of the initial analysis cycle was to establish a baseline set of actuator slip levels and lunge rate, without the use of Post-Contact Thrusting (PCT), that predicted overall favorable results. Both light↔light and heavy↔heavy mass property configurations were simulated, and a set of SIMAC parameters was identified that resulted in acceptable loads and nearly 100% capture success performance. A single light↔light simulation case failed to capture and the maximum actuator stroke required was longer than desired.

### 2. Sensitivity Studies

The simulations conducted after the initial analysis focused on studying the effect of varying the slip levels, lunge rate and ready-to-capture height to improve capture performance, reduce the required actuator stroke, and establish performance with some tolerance to variation in slip level and lunge rate. Sensitivity studies to variation in



the slip levels and lunge rate were executed, resulting in the increase in the lunge slip level to 15 lb, an increase in the lunge rate to 4 inch/sec, an increase in the attenuate slip level to 80 lbs, and a reduction of the the ready-to-capture height by 7 inches, from the initial height assumed during the OSP program.

These simulations showed that if the active capture ring extends relatively slowly, then the loads from impacting the passive ring and from forcing compliance will be low; however, there will consequently be more time for the vehicles to be pushed apart before full active⇌passive ring compliance and capture takes place. More time spent in lunge translates into a longer actuator stroke being required, or a failed capture attempt if the stroke is insufficient. However, if the active capture ring extends relatively quickly, then full compliance and capture will be assured, the required stroke will be reduced, but the loads from impact and compliance will be higher.

In concert with the actuator lunge rate, the lunge mode slip level has a significant impact on the success of a capture attempt. If the slip level is set too high, the active ring is less effective at physically complying to the passive ring in the face of relative initial conditions and the active ring tends to push away the passive ring, rather than capturing it. If the slip level is set too low, the active ring is incapable of overcoming the assumed capture latch resistance and is never able to successfully capture.

The final set of simulation in this cycle resulted in 100% capture performance, with acceptable interface loads and acceptable maximum actuator strokes, and with linear actuator slip and lunge rate settings that deemed feasible, according to vendors Boeing was consulting with.

### *3. Monte Carlo Simulations*

In order to evaluate performance in a way that more accurately represented actual distribution of ICs, a set of 100 ICs were generated using a normal distribution assumption for most of the IC parameters. Notably, both the range and the absolute limits on the relative approach rate utilized in the set of simulation was reduced, compared to previous simulations. Once again, the results of these simulation also showed 100% capture success, satisfaction of the interface load limitations and tolerable maximum actuator strokes.

### *4. Extreme ICs*

A 2<sup>nd</sup> set of extreme ICs was requested by the NASA customer to check performance at the extremes of the NDS IDD initial condition limits, together with the lower range of approach rates. A set of 17 ICs with similar sets of parameters, except lower approach rates, was simulated in order to assess performance. While performance was 100% satisfactory for the heavy⇌heavy vehicle pair, there were 3 capture failures in the light⇌light vehicle pair: those cases with a combination of worst-case offsets in multiple parameters simultaneously.

However, increasing the relative approach rate by 3 cm/s across the board for all 17 cases resulted in 100% capture success, with all interface loads remaining within requirements and actuator strokes still acceptable.

The most significant unknown cited by linear actuator vendors, regarding the performance of the linear actuators, was the ability of the actuators to maintain the desired slip levels and lunge rate within specified tolerance in the face of varying friction levels due to the variation of temperature in space. As the study neared conclusion, this was identified as the most significant risk to success for the SIMAC concept.

## **V. Conclusion**

Suitability of the SIMAC as the soft capture system for the NASA Docking System was explored through a series of analyses using multi-body dynamics simulations. Although it was initially developed in support of the prior NASA OSP program, linear actuator performance parameters were successfully adjusted to demonstrate 100% satisfactory capture success, interface loads and actuator stroke, utilizing NASA-directed initial conditions, relative vehicle masses and constraints on the interface loads. Preliminary design efforts by both Boeing and linear actuator vendors concluded that actuators with the final, assumed performance characteristics were predicted to be manufacturable. The remaining risk and concerns regarding the performance of vendors' proposed linear actuators in the face of varying friction would later be removed via proof of concept testing, careful design work, and engineering development unit hardware tests. These topics will be likely be described in a future paper.

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