A Proposed Strategy for the U.S. to Develop and Maintain a Mainstream Capability Suite ("Warehouse") for Automated/Autonomous Rendezvous and Docking in Low Earth Orbit and Beyond

NASA AR&D Community of Practice

BASELINE

February 2012

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Revision	**Date**	**Change Summary**
BASELINE	Feb 2012	Original baselined document.

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A Proposed Strategy for the U.S. to Develop and Maintain a Mainstream Capability Suite ("Warehouse") for Automated/Autonomous Rendezvous and Docking in Low Earth Orbit and Beyond[1]

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Overview

The ability of space assets to rendezvous and dock/capture/berth is a fundamental enabler for numerous classes of NASA's missions, and is therefore an essential capability for the future of NASA. Mission classes include: ISS crew rotation, crewed exploration beyond low-Earth-orbit (LEO), on-orbit assembly, ISS cargo supply, crewed satellite servicing, robotic satellite servicing / debris mitigation, robotic sample return, and robotic small body (e.g. near-Earth object, NEO) proximity operations. For a variety of reasons to be described, NASA programs requiring Automated/Autonomous Rendezvous and Docking/Capture/Berthing (AR&D) capabilities are currently spending an order-of-magnitude more than necessary and taking twice as long as necessary to achieve their AR&D capability, "reinventing the wheel" for each program, and have fallen behind all of our foreign counterparts in AR&D technology (especially autonomy) in the process. To ensure future missions' reliability and crew safety (when applicable), to achieve the noted cost and schedule savings by eliminate costs of continually "reinventing the wheel", the NASA AR&D Community of Practice (CoP) recommends NASA develop an AR&D Warehouse, detailed herein, which does not exist today. The term "warehouse" is used herein to refer to a toolbox or capability suite that has pre-integrated selectable supply-chain hardware and reusable software components that are considered ready-to-fly, low-risk, reliable, versatile, scalable, cost-effective, architecture and destination independent, that can be confidently utilized operationally on human spaceflight and robotic vehicles over a variety of mission classes and design reference missions, especially beyond LEO. The CoP also believes that it is imperative that NASA coordinate and integrate all current and proposed technology development activities into a cohesive cross-Agency strategy to produce and utilize this AR&D warehouse.

An initial estimate indicates that if NASA strategically coordinates the development of a robust AR&D capability across the Agency, the cost of implementing AR&D on a spacecraft could be reduced from roughly $70M per mission to as low as $7M per mission, and the associated development time could be reduced from 4 years to 2 years[2], after the warehouse is completely developed. Table 1 shows the clear long-term benefits to the Agency in term of costs and schedules for various missions. (The methods used to arrive at the Table 1 numbers is presented in Appendices A and B.)

Table 1 - Steady-State AR&D Costs Per Vehicle

Vehicle Mission	*Without* Integrated Agency Strategy	*With* Integrated Agency Strategy
LEO to non-ISS (e.g. satellite servicing, on-orbit assembly)	$65.6M[‡] 4 years	$6.6M[‡] 2 years
LEO to ISS (dual string, human rated)	$83.4M[‡‡] 5 years	$20.0M to $8.4M[‡] 2 years
Beyond LEO	$56.2M[‡‡] 4 years	$28.8M to $10.0M[‡‡‡] 2 years

[1] Authored by the AR&D Community of Practice, a collaboration among ARC, DFRC, GRC, GSFC, JSC, JPL, LaRC, MSFC, and the NESC.

[2] Crain, "Business Case for a Campaign of NASA AR&D Development", EG-DIV-10-022, June 2010.

Looking at these numbers, the impact is enormous, particularly for lower cost missions. It is conceivable that the final warehouse could make future missions in the $300M and less category much more viable. At an Agency level, as described earlier, numerous future NASA missions will require AR&D. If we assume 6 new vehicles going to LEO (2 to ISS, 4 non-ISS), and 2 going beyond LEO, in the next ten years, that results in an Agency savings of roughly $520M and 16 development-years over that decade. Each vehicle also has a significant risk reduction in technical performance as time progresses.

There is no single mission that can achieve all AR&D capabilities needed to populate the AR&D warehouse and enable all mission classes, rather a campaign of coordinated missions will be needed to exercise and develop all AR&D-enabling capabilities, as Figure 1 shows. Agency-level direction which coordinates technology development over multiple space-based demonstration missions, each leveraging on the prior, is required to achieve an AR&D warehouse solution for the wide spectrum of future U.S. human and robotic missions. To achieve these long-term savings, some minimal Agency-level investments will be required by the earliest programs to adopt this strategy, as this approach will not be the most cost-effective solution for them, i.e. their cost may be slightly higher than those shown in the middle column of Table 1. (One quick look comparison between the same proposal with and without using the Warehouse led to a "negligible" change in cost[3]. Since incurred delta-costs will necessarily be non-zero, we use the term "minimal" when referring to the additional costs involved, especially relative to the current design costs shown in the middle column of Table 1.) This is precisely why we are where we are in terms of our history of point-designs and their obsolescense - this can only be overcome by Agency leadership and investment. All of this is discussed in further detail below.

	ISS Crew Rotation (LEO)	Crewed Exploration Missions Beyond LEO	On-Orbit Assembly	ISS Cargo Supply	Satellite Servicing (w/crew)	Satellite Servicing / Debris Migitation (robotic)	Sample Return (robotic)	Small-Body (NEO) Proximity Operations (robotic)	
Characteristics of Foundational (Less Difficult) Missions									Characteristics of Advanced (More Difficult) Missions
Human (non-Automated)									Computer (Automated)
Ground-Dependent (non-Autonomous)									Onboard Capable (Autonomous)
Designed for Docking/Capture									Not Designed for Docking/Capture
Target Geometry Known									Target Geometry Unknown
Target Dynamics Fixed/Known									Target Attitude Tumbling/Unknown
Number of Vehicles = 2									Number of Vehicles > 2
Fail-Safe									Fail-Operational

Figure 1 - AR&D Characteristics and Order of Difficulty vs. Mission Class (Notional)

(Yellow Indicates that Mission Class' AR&D Systems Tend to Have Characteristics of Foundational [Less Difficult] Missions Listed in the Left Column, Orange Indicates a Tendency Toward Characteristics of Advanced [More Difficult] Missions Listed in the Right Column)

Not only will the Agency achieve enormous cost and schedule savings, but future missions would also see significant risk reductions in technical performance as the Warehouse develops. It should be noted here that NASA leadership in establishing an AR&D warehouse will also benefit proposed Department of Defense (DoD) missions and will benefit the commercial sector as well. The NASA AR&D CoP believes the AR&D Warehouse is a highly desired outcome, achievable in the next five to ten years. A strong commitment by Agency leadership to a strategic Agency direction based on an evolutionary, stair-step development, through a campaign of coordinated ground tests and space-based system demonstrations of AR&D component technologies, will yield this multiple-use AR&D warehouse and its associated benefits.

[3] Hunt, "RE: OCFO Support for the Autnomous Rendezvous, Docking, and Close Proximity Ops," e-mail communication, January 17, 2012.

We also note that at the point of finalization of this document, the team discovered a very similar study done in 2004 that note makes many of the same points[4]. Where parallels exist, reference will be made to this study.

Before proceeding, we discuss possible paths outside of NASA. Although it may be attractive to purchase AR&D capabilities abroad, if foreign and/or commercial systems were employed by NASA vehicles, there would be the risk of limited insight into their designs, limits on our vehicles as dictated by their designs, as well as ownership and/or technology transfer issues. Reference 4 points out "*The Europeans and Russians do not have hardware or technology that is appropriate (too heavy, high mating forces, etc.) to use or adapt for the Exploration Initiative*". Even partnering with the DoD presents obstacles in the form of security clearances. Thus, we believe a NASA-developed warehouse is critical to NASA's future.

The remainder of this paper discusses the problem of continually reinventing the A&RD wheel and the proposed solution of 1) implementing an Agency-integrated strategy, and 2) developing an AR&D Warehouse. The risk of inaction is shown and a summary. We begin though, with clarifying remarks on autonomy and automation.

Autonomy and Automation Defined

Before proceeding, it is prudent to clarify the AR&D CoP definitions of autonomy and automation. By "autonomy" or "autonomous", we are distinguishing between ground dependency and onboard capability for a given function. That is, a fully autonomous function can be executed onboard using a combination of crew and onboard software, without ground support; a fully non-autonomous function requires ground support using a combination of flight controllers and ground software. By "automated" or "automation", we are distinguishing between computer and human operation. A fully automated function is done completely by computers (onboard and/or ground); a fully non-automated function is done completely by humans (crew and/or flight controllers). Given these definitions, we can characterize the split between onboard flight computers (autonomous/automated), onboard crew (autonomous/non-automated), ground computers (non-autonomous/automated), and humans on the ground (non-autonomous/non-automated), and all "shades of grey" in between, which varies greatly based on function. Figure 2 shows a notional example of the distinction between autonomy and automation.

The Problem – Our History of Obsolescense

In spite of a significant track record of successful rendezvous and docking missions to the ISS involving varying degrees of AR&D capability, and other successful demonstration missions of limited AR&D capability, a U.S. mainstream AR&D technology base for a wide spectrum of missions does not exist. ("*None of the elements of an automated rendezvous and docking system currently exist in flight-ready systems in the United States*."[4]) To date, all U.S. programs have generated point-designs with limited application. ("*Present technology for rendezvous is mission unique, and requires extensive human in the loop activity for flight operations and ground control, resulting in cost and schedule impacts*."[4]) For example, full autonomy and automation has not been required for LEO rendezvous and docking missions as yet, because these missions take advantage of ground and space-based assets ("*Virtually all rendezvous' and dockings (R&D) performed by the United States to date have utilized crew-in-the-loop and ground controller assistance…. The United States has not yet performed an AR&D mission*."[4]) - in effect, missions implement varying degrees of autonomy and automation that are tailored for their purposes. Thus, new missions requiring AR&D capabilities continue to incur significant non-recurring

[4] Winkler, Roberts and Vaught, "Autonomous Rendezvous and Docking White Paper and Final Report", Capability Requirement Analysis and Integration (CRAI) Independent Assessment Team, June 2004.

engineering (NRE) and development costs related to AR&D component sensors and integrated systems, and the systems developed are point designs - even worse, designs that become obsolete after each mission is flown.

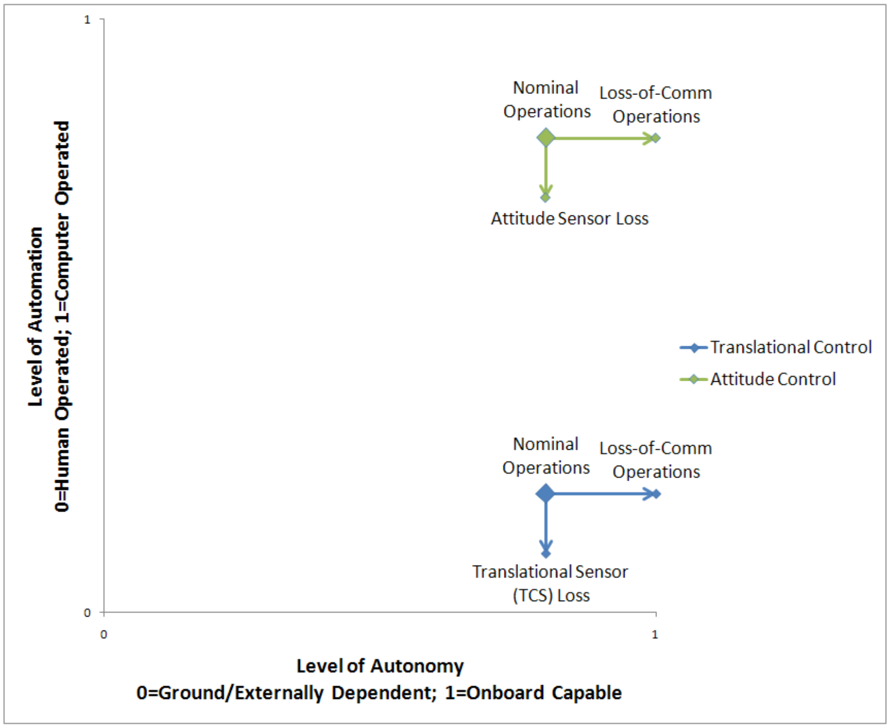

Figure 2 - Notional Example Levels of Autonomy and Automation for Shuttle Final Docking Approach, for Both Translational and Attitude Control

For example, for the past three decades the Space Shuttle exclusively provided American operational rendezvous and docking capability. While Space Shuttle rendezvous activities have been 100% successful, they have been limited to LEO operations and heavily utilized ground operators and the flight crew to increase mission success probability and robustness to failures. In recent years, several AR&D technology demonstrators such as Orbital Express and XSS-11 have flown successful or partially successful Rendezvous, Proximity Operations, and Docking (RPOD) missions with intentionally limited human involvement from ground controllers. These missions were also intentionally limited in scope and capability, and had no clear long-term impact as they were not part of an overall coordinated strategy. In fact, much of the hardware demonstrated on these missions is no longer available to support future flights. Operational ISS transport and re-supply is currently provided by AR&D systems in the form of ATV, HTV, and Progress, by the Europeans, Japanese, and Russians respectively, and in the future by the U.S. through the Orion/MPCV spacecraft and/or commercial vendors. All these systems are necessarily optimized to take advantage of LEO infrastructure, such as GPS and ready-access to ground controllers, and are therefore not extensible to applications beyond LEO without significant NRE.

The capabilities developed for each vehicle and mission simply do not outlive their projects. They become obsolete and are of limited or no use to future programs, so new NASA projects are continually reinventing the wheel of AR&D. The primary reason for this “history of obsolescense” is a lack of an integrated Agency-wide AR&D technology development strategy that drives programs to long-term Agency-wide solutions versus program point designs, and funding the additional minimal resources to the programs that this takes in the short-term.

The Solution, Part 1 – Integrated Agency AR&D Strategy

Broad Agency support and funding for an evolutionary, stair-step development through a campaign of space-based system demonstrations of an AR&D capability suite that supports the spectrum of Agency exploration missions is required. As capabilities continue to be developed, it may not always be in the best interest of individual Programs to help advance these capabilities, especially in terms of maintaining the versatility of the system. If upcoming missions simply tailor recent LEO demonstration systems to fit their specific needs, their contribution to future planned missions will be minimal, as we have seen in the past. The Agency will also have to commit to continual reassessment of this AR&D strategy, making adjustments as needed. The Agency will also have to actively coordinate AR&D efforst at various centers, because, as noted in Reference 3, "*An integrated program to develop and demonstrate AR&D hardware and software for the Exploration Initiative does not currently exist…An AR&D Program formulation plan needs to be developed… The lack of top-level requirements, guidelines, ground-rules, expectations and design reference missions is a clear impediment to the orderly pursuit of preliminary systems designs*" across centers. The OCE and NESC will support all continued efforts to ensure continual Agency support and manage overall integrated Agency AR&D success.

The Solution, Part 2 - The Warehouse / Toolbox / Library Concept

Before proceeding, it must be noted that the idea of an AR&D warehouse is not one of standardizing AR&D. Rather, the concept is a library or toolbox of reusuable AR&D GN&C algorithms, coupled with reusuable mission manager algorithms and supply-chain hardware components, all integrated with standardized interfaces. Only the interfaces are standardized. Although it would be highly desired, it is impractical to design a "universal" AR&D warehouse that meets 100 percent of the needs for every mission. Therefore, the goal is to provide an AR&D toolbox with approximately 80 percent of the capability needed for any mission and flexible interface standards that allow each mission to tailor the remaining 20 percent of their flight design based on unique mission needs.

The warehouse achieves the 80 percent capability by first compiling a comprehensive set of AR&D software and algorithm libraries, illustrated in Figure 3, which represent the state-of-the-art from NASA organizations. The software and algorithm libraries are accompanied by AR&D flight processors and emulators, docking/berthing/capture system emulators, and interface control documents (ICDs). Integrated together with standardized interfaces and supply-chain hardware, this AR&D warehouse provides the ability to construct cohesive AR&D flight system configurations, or instantiations, very rapidly, for all of NASA's future robotic and human missions requiring AR&D.

Each element of the AR&D warehouse is evolvable allowing advances in sensor technology, computer technology, and algorithms to be integrated with a minimum of difficulty. Since the majority of the effort in an AR&D mission is solving the complex systems integration challenges, the 80 percent off-the-shelf solution delivered by the warehouse greatly reduces the NRE costs for each mission compared to business-as-usual.

Note that no project is forced to use any of the warehouse. When a new mission sets out to develop its AR&D system, or a mission concept team sets out to quickly model its AR&D system, those involved simply pull what they want from the warehouse "toolbox" or "library". If they choose, they can use nothing from the AR&D warehouse, and start out with less than 10% of their design. Or if they pull one of each category of items in the toolbox, they could end up with as much of 80% of their design. After their design is complete, they place any newly developed items back into the warehouse for future missions' use.

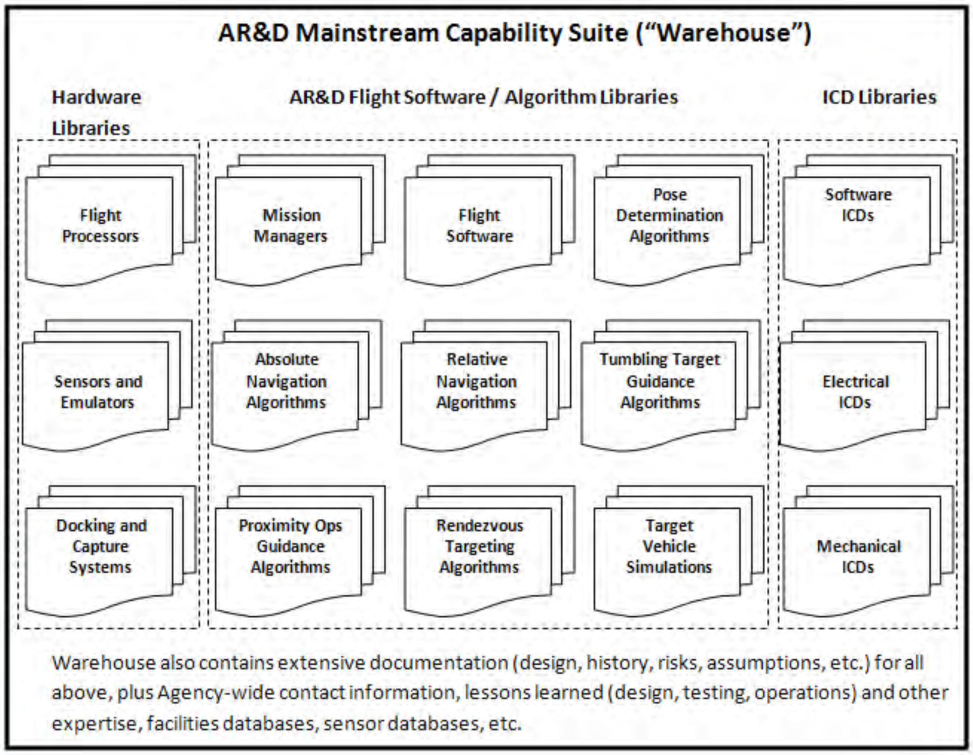

Figure 3 – AR&D Mainstream Capability Suite ("Warehouse")

The warehouse would need to have two categories assigned to each item within. The first would be categories similar to TRLs to distinguish developmental items at one extreme versus items with flight heritage at the other. The second would be to distinguish open source items versus other classifications. The goal is to maximize the open-source nature of the items in the warehouse. At a minimum, items in the warehouse shall meet "open-interface" standards – even if an item is a "black box" because of contractual, proprietary, or other restrictions, other elements of the warehouse will be able to utilize that item, for any program that wishes to use such an item. This will enable sharing of items across NASA and DoD and our industry partners. Figure 4 shows how this might be done. The AR&D CoP has received initial interested from AFRL, and believes DARPA will also be interested in working with NASA on the AR&D Warehouse concept. In fact, a similar concept to the AR&D warehouse development is already underway at DARPA's Tactical Technology Office within the System F6 project[5].

The AR&D CoP will also provide support via its network of experts to projects to assist them in utilizing, and later contributing to, the warehouse.

It is important to clarify that AR&D is not a system and cannot be purchased off the shelf. Rather, AR&D is a *distributed capability* that requires many vehicle subsystems to operate in concert, as shown in Figure 5. ("*AR&D is a required long-lead item … with a significant interplay with other vehicle systems. It must be treated as a systems problem*." [4])

Thus, AR&D leverages the complete vehicle capability through the systems engineering and integration of multiple subsystems. For this reason, our proposed strategy does not focus on development of a single complete

[5] http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx.

AR&D package capable of being wired into a spacecraft which supports all mission types in Figure 1 ("AR&D-in-a-box"). Instead our strategy focuses on development of an AR&D capability suite, which primarily involves four specific subsystems, that can enable AR&D and its required integration for all these missions. These four subsystems are those which are most impacted by adding an AR&D requirement to a vehicle: GN&C, Mission Manager, Sensors, and of course the Docking System which is not required at all without AR&D. (Note that all other subsytems, e.g. propulsion, C&DH, etc., would be part of any vehicle, even those that do not rendezvous.)

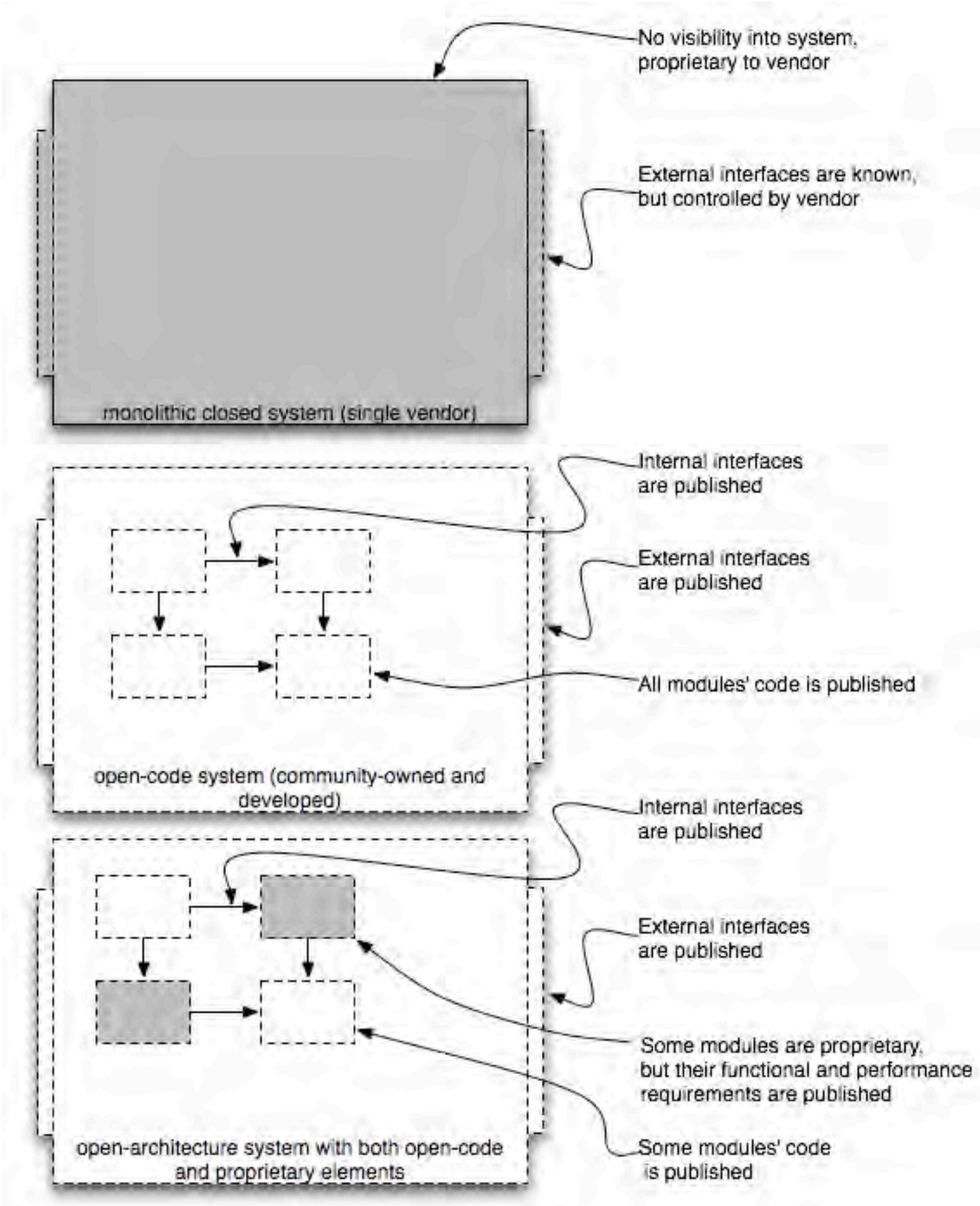

Figure 4 – An Illustration of How the AR&D Warehouse Could Use Both Open-Source and Closed-Source Elements

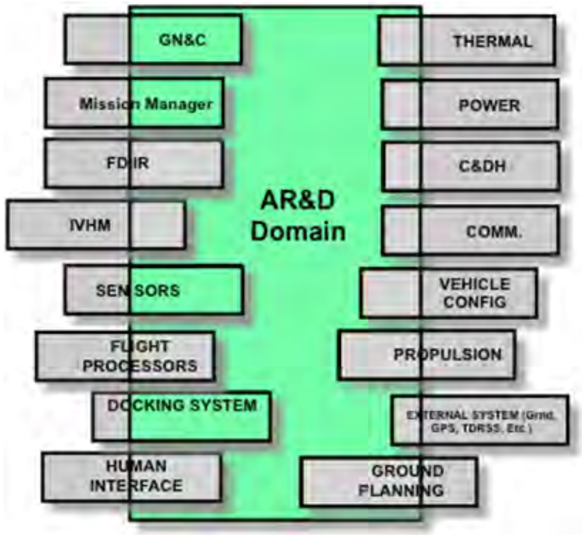

Figure 5 - AR&D is a Really an Integration of Many Subsystems; Four are AR&D-Specific (Shown in Green)

The AR&D capability suite would be populated with various solutions for each of these four areas, and all solutions would have standardized interfaces (e.g. the recently agreed-to "International Docking System Standard"[6]). Then, each mission would then pick-and-choose which solutions in the AR&D suite are most useful for implementing their design. Focusing on the four subsystems that are most impacted for any AR&D mission:

1) *Relative Navigation Sensors and Integrated Communications* – During the course of RPOD, varying accuracies of bearing, range, and relative attitude are needed for AR&D. Current commercial implementations for optical, laser, and RF systems (and combinations of these) are mid-TRL (Technology Readiness Level) and require flight experience to gain reliability and operational confidence. Moreover, integrated communication capability (at mid-field to near-field range) greatly enhances the responsiveness and robustness of the AR&D GN&C system, along with its portability.

2) *Robust AR&D GN&C & Real-Time Flight Software (FSW)* – Space Shuttle, Orbital Express, XSS-11, and other development efforts have raised the maturity of AR&D GN&C algorithms to a very high level for these point designs. However, to develop and refine these point design algorithms into a robust AR&D GN&C system capability, integrated with the high-level Mission/System Managers (item 4 below), and implemented into realtime FSW is an enormous challenge. A best-practices based implementation of an AR&D GN&C system into real-time FSW operating systems does not exist.

3) *Docking/Capture Mechanisms/Interfaces* – NASA is planning for the imminent construction of a new low-impact docking mechanism built to an international standard for human spaceflight missions to ISS. A smaller common docking system for robotic spacecraft is also needed to enable cost-efficient robotic spacecraft AR&D. Assembly of the large vehicles and stages used for beyond LEO exploration missions will require new mechanisms with new capture envelopes beyond any docking system currently used or in development. Berthing methods may also be utilized when warranted by mission requirements. Furthermore, for satellite servicing/rescue, development and testing is needed for the application of autonomous robotic capture of non-cooperative target vehicles in which the target does not have capture aids such as grapple fixtures. AR&D capability must be compatible with the capture envelopes of all of these systems.

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[6] "International Docking System Standard (IDSS), Interface Definitions Document (IDD)", September 2010.

4) *Mission/System Managers for Autonomy/Automation* – A scalable spacecraft software executive that can be tailored for various mission applications and various levels of autonomy and automation, as enabled by the robust AR&D GN&C system (item 2 above), is needed to ensure safety and operational confidence in AR&D software execution. A scalable and evolvable executive architecture will prevent each mission from reinventing this critical piece of the AR&D software. Numerous spacecraft software executives have been developed, but the necessary piece that is missing is an Agency-wide open interface standard which will minimize the costs of such architectures. Creation of such a standard is also critical to ensure an ability of these architectures to leverage lessons learned and to evolve to higher levels of autonomy/automation over time as trust increases gradually in these capabilities. This evolutionary trait is especially critical to the trust of, and therefore success of, AR&D on crewed vehicles. Advances in fault management techniques must also be made in parallel. Reference 3 states "*Autonomous Flight Manager software is essential for all autonomous vehicle subsystems, including AR&D, and may well prove to be the most difficult development task for the Exploration Initiative*."

None of these subsystems are low TRL by themselves; the immaturity is in the integration. Some are not mature enough to be considered for further development and refinement into an AR&D warehouse. This will require both ground testing and on-orbit demonstrations, as well as incorporation of lessons learned through integration with other subsystems on a variety of spacecraft before they can all be considered part of a U.S. AR&D warehouse.

The AR&D CoP believes that once an AR&D warehouse is established, its application to future Programs will save significant NRE costs, avoid considerable schedule delays, and significantly reduce technical risk. The Programs could tailor (and even enhance) these capabilities with minimal investments. In the long term, this represents a substantial savings in cost, schedule, and technical risk to each Program and subsequently to the Agency overall. This is especially important from an Agency perspective as the savings multiply by the number of AR&D missions. Development of a U.S. AR&D warehouse consists of three elements:

1) Initial maturation of the four subsystem technologies (relative navigation sensors and integrated communication, robust AR&D GN&C & real-time FSW, docking/capture mechanisms, and mission/system managers). This can be addressed in relatively short order with the judicious coordination of ongoing Program efforts and new funding. Leveraging the RPOD accomplishments of previous Programs, heritage GN&C algorithms, and software will be utilized to minimize development costs. Existing mission manager software will be used initially as a baseline to create a flexible and configurable system to support future vehicle architectures. NASA has already invested significant resources toward the NRE development costs for pertinent navigation sensors required for AR&D. This first element involves both ground and flight testing, provides NASA with hands-on experience, establishes the architecture for the capability suite, and lays the groundwork for commercial application.

2) Achieve an understanding of the integration and interplay of AR&D with various subsystems, while meeting vehicle and mission requirements and constraints. This is our most significant challenge. The vast majority of the AR&D development effort involves recognizing and dealing with contingencies and unexpected behavior from subsystem interaction and off-nominal conditions. So, in addition to architecting the AR&D GN&C system to maximize robustness (through well-designed FDIR and contingency responses) and minimize such subsystem interaction/dependencies (i.e., keeping clean interfaces by design), we must accumulate operational experience, confidence, and history with these systems and capabilities through ground testing as well as multiple space-based system demonstrations to lower the risk for each mission. The focus for AR&D technology development can be reduced to two steps. First, re-use, extend, and update current

mature capabilities. Second, fill and enhance the remaining technology gaps, such as enhancing autonomy through systematic fail-operational approaches, enhance mission manager re-planning and re-configuration response capabilities, incorporation of robust AR&D GN&C algorithms into real-time FSW, and extension of these algorithms to support missions beyond LEO.

3) Development of supply chains for AR&D hardware. A very large portion of the cost reductions estimated herein is due to use of hardware made available through a stable supply chain. As mentioned, our history is one of AR&D hardware developed for single-use applications. In the case of standardizing docking mechanisms for larger spacecraft, the Agency is already moving forward with changing this paradigm. We have many more opportunities however to ensure that hardware is available for multiple uses. For example, three separate flash LIDAR experiments have flown on the Space Shuttle in recent years. NASA should take steps to ensure that all three continue in development and remain available for selection by programs, "off-the-shelf", as all three have their applications depending on program requirements. But none will ever be selected if the supply is not there. The classes of sensors of use to AR&D can be generally grouped according to:

    a. Long range RF devices: At distances of 1-1,000+ km RF signals between AR&D spacecraft are used to support rendezvous maneuvers with timely state updates.
    b. Long range optical devices: At distances of 1-1,000+ km optical bearing measurements may be accumulated in time to support rendezvous maneuvers.
    c. Medium range optical and laser devices: At distances in the transition between rendezvous and proximity operations (1-30 km) optical and laser devices can be used to directly measure relative translational states.
    d. Short range optical and laser devices: At distances appropriate for proximity operations (< 5 km to dock) optical and laser devices may provide both translation and orientation state information

Risk of Inaction

Thus far, we have attempted to establish these four items: 1) there is no current off-the-shelf versatile AR&D capability, 2) technology components (such as sensors) developed for previous missions often no longer exist in a production capacity and/or they were most likely designed with specific missions in mind and would require extensive redesign, 3) foreign and commercial systems are not viable for this same reason, in addition to complications from limited insight in their designs and limits on our vehicles as dictated by their designs, and 4) AR&D's level of dependency on other systems. Assuming there is agreement on these four items, then, without Agency-level direction, coordination, commitment, and investments to get an AR&D warehouse, it is reasonable to assume that new Programs requiring an AR&D capability must continue to develop their own AR&D components, "reinventing the wheel" for each mission, developing their own tailored/custom, sufficient AR&D systems. They will continue to be burdened with the associated significant NRE, schedule, and technical risk. NASA will perpetuate the history of obsolescence and prevent the maturation of an Agency capability suite which would reduce these risks for future Programs. *The penalty of not establishing an Agency-level coordinated strategy now is significant long term additional cost, increased development time, and increased risk for future Projects. Additionally, the Agency will miss an opportunity to address our needs, influence the commercial sector, and will fall ever further behind our foreign counterparts.*

Strategy Implementation Relative to Orion/MPCV

Arguing the implementation of this strategy through various NASA Programs is not a purpose of this white paper. However, the AR&D CoP has been asked to specifically address the potential role of Orion in the Agency implementation. If the Agency directed Orion (or any other current Program) to become part of this Agency strategy, Orion could become one of the viable and crucial first steps in the overall evolutionary, stair-step development effort. As an example, to implement this utilizing an Orion that will go to ISS, minimal additional Agency-level investments would be required and additional strategic AR&D requirements would need to be levied on Orion and ISS. Without such Agency level redirection, Orion will surely optimize its AR&D subsystems for their mission specific LEO operations (e.g. taking advantage of GPS, TDRSS, and ground support that would not be available for other mission classes). As Figure 1 shows, a*n Orion design optimized for an ISS mission will not fully provide all AR&D needs for the NASA portfolio of missions over the next 10-15 years.* However, with Agency investments and proper re-direction, NASA can utilize Orion in mutually developing a system that is extensible to human and robotic missions beyond LEO and build a more complete solution which is reusable. This benefit would be gained even if Orion does not go to ISS, and even if we chose a different vehicle for our example. As a result, when coupled with additional investments in other Programs, Orion's AR&D system would satisfy the Agency's first-step objectives, and ensure that Orion would complement the overall strategic path to an AR&D warehouse for the Agency.

Progress Thus Far and Immediate Next Steps

Significant progress has been made already in achieving agreement with the strategy outlined herein. First, the AR&D Community of Practice has led AR&D practitioners at eight NASA centers and the NESC to come to agreement on this strategy. This paper has been presented and endorsed and/or agreed to by the Agency's Flight Sciences Steering Committee, the Agency Chief Engineer, the GNC Technical Discipline Team, and the NESC Review Board. The Office of Chief Technologist adopted the bulk of its TA4 Roadmap (insert reference!) from early drafts of this whitepaper, and drafted its 2010 Broad Area Announcement call in the area of AR&D also from early drafts of this document. Early in CY2012, the CoP will incorporate any public and industry feedback that OCT received from its roadmaps, and then will release this full whitepaper to the DoD and the public via publication and solitic additional feedback and support.

While implementation details are not the subject of this whitepaper, once fully adopted, the CoP will formulate recommendations for implementation if requested. In parallel, the initial development of the warehouse can go forward, and it has. The warehouse concept has already received $225k in institutional funds from the centers to begin building the warehouse and the standardized interfaces necessary. An initial demonstration of the warehouse was performed in September 2011. The CoP hopes to acquire additional funding to complete the initial development of the warehouse and to demonstrate it, especially its algorithm modularity and capability to run in multiple environments and testbeds in FY2012.

The CoP will also be looking for a low cost flight opportunity. Once the warehouse is successfully used for a flight, the cost savings will be calculated and used to refine the projected costs already mentioned in this whitepaper.

Summary

The AR&D CoP recommends that the Agency make the necessary commitments and investments to implement a cohesive cross-Agency strategic direction for AR&D, that is based on evolutionary stair-step development through a campaign of coordinated ground tests and space-based system demonstrations, to achieve a mainstream AR&D capability suite, or “warehouse”, that supports the spectrum of future Agency exploration missions. The Agency should coordinate and integrate all ongoing and future technology and development Programs, including investing additional (minimal) resources and levying additional strategic AR&D requirements on current Programs, as necessary, such that current Programs are fully integrated into this Agency strategy. The CoP believes that with this approach, a U.S. mainstream AR&D technology base for a wide spectrum of missions can be developed that is ready-to-fly, low-risk, reliable, versatile, architecture and destination independent, and extremely cost-effective, perhaps reducing AR&D implementation costs from roughly $70M per mission to as low as $7M per mission. This capability would enable the future missions of the Science, Space Operations, and Exploration Systems Mission Directorates, would benefit the DoD and the commercial spaceflight sector, and would re-establish U.S. leadership in the AR&D community.

Appendix A - Business Case for a Campaign of NASA AR&D Development

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NASA Johnson Space Center
EG - Aeroscience and Flight Mechanics
Internal Memorandum

Date: **June 15, 2010** **Document Number: EG-DIV-10-022**

Subject: Business Case for a Campaign of NASA AR&D Development

The purpose of this memorandum is to illustrate how a campaign of Automated/Autonomous Rendezvous and Docking (AR&D) development missions will both raise the technology readiness level (TRL) of overall AR&D and reduce the recurring cost for NASA and non-NASA deployment of missions with AR&D capability. This paper assumes an Agency-wide approach that leverages off of the synergy of Orion Project development, the Flagship Technology Demonstration Program, and ISS servicing needs. Note that the Flagship Technology Demonstration Program is used as an example to leverage missions of opportunity for improving AR&D capability but is not explicitly necessary. In fact, any campaign of missions with development allocations for AR&D could be utilized. Such an AR&D Development Program could reduce the mission-to-mission AR&D capability cost to as little as $6,000-9,000k per mission.

The information contained herein includes cost estimates and assumptions that are gathered from both ongoing and previous NASA projects and should be considered sensitive in nature.

Prepared by:

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1.0 Introduction

Consideration of all of NASA's development efforts and mission needs indicates that an Agency level approach to AR&D capability is warranted. This paper considers the benefit of coordinating Orion Project Rendezvous, Proximity Operations, and Docking (RPOD) development and Flagship Technology Demonstration (FTD) Program development to meet the needs of ISS logistics missions, SMD large scale science missions, and ESMD human exploration missions to yet-to-be-defined Beyond Earth Orbit (BEO) destinations. Thus, an "AR&D Development Program" is proposed.

The Orion Project is pursuing RPOD to provide ISS transportation and crew return and as an enabling method for assembly with planetary transportation systems. In parallel, NASA is developing plans for a Flagship Technology Demonstration (FTD) Program of missions [1] intended to raise the TRL and operational availability of a number of key technologies such as:

- Automated/autonomous rendezvous and docking
- Advanced Solar Electric Propulsion (SEP)
- Lightweight/Inflatable Modules
- Aerocapture, and/or entry, descent and landing (EDL) technology
- Closed-loop life support system demonstration at the ISS
- In-Orbit Propellant Transfer and Storage

The FTD Point-of-Departure (POD) plan is to execute 4 missions in the next 5 years with primary mission objectives to advance inflatables, in-space propellant depots, SEP, and aerocapture as illustrated in Table 1. This proposal uses the FTD Program as a framework to show how a campaign of AR&D development could be implemented for cost reduction and improved readiness. However, the FTD Program could be replaced by any coordinated series of missions with development allocations for supporting AR&D development.

Table 1: FTD Point-of-Departure Flight Manifest

Key Technology / Launch	FTD-1 SEP	FTD-2 Propellant Storage	FTD-3 Inflatable	FTD-4 Aerocapture
Prop Transfer/Storage		X		
Inflatable Modules			X	X
AR&D	X	X	X	
ECLS			X	
Adv. Space Prop	X			
Launch Date	2014	2015	2016	2015

Note that three of these missions contain AR&D components. The FTD POD philosophy was to integrate AR&D maturity throughout multiple missions to achieve maturity and reliability rather than target a single "AR&D" demonstration flight. This maturation approach is illustrated in Figure 1 where the key AR&D component technologies of mission management software, relative navigation sensors, GN&C algorithms, and docking mechanisms are specifically highlighted for each mission.

The following sections include, in addition to the Orion and FTD considerations, an examination of the recurring cost of deploying the resultant NASA AR&D technology base for missions such as node delivery to ISS and large-scale science mission assembly as part of an integrated approach.

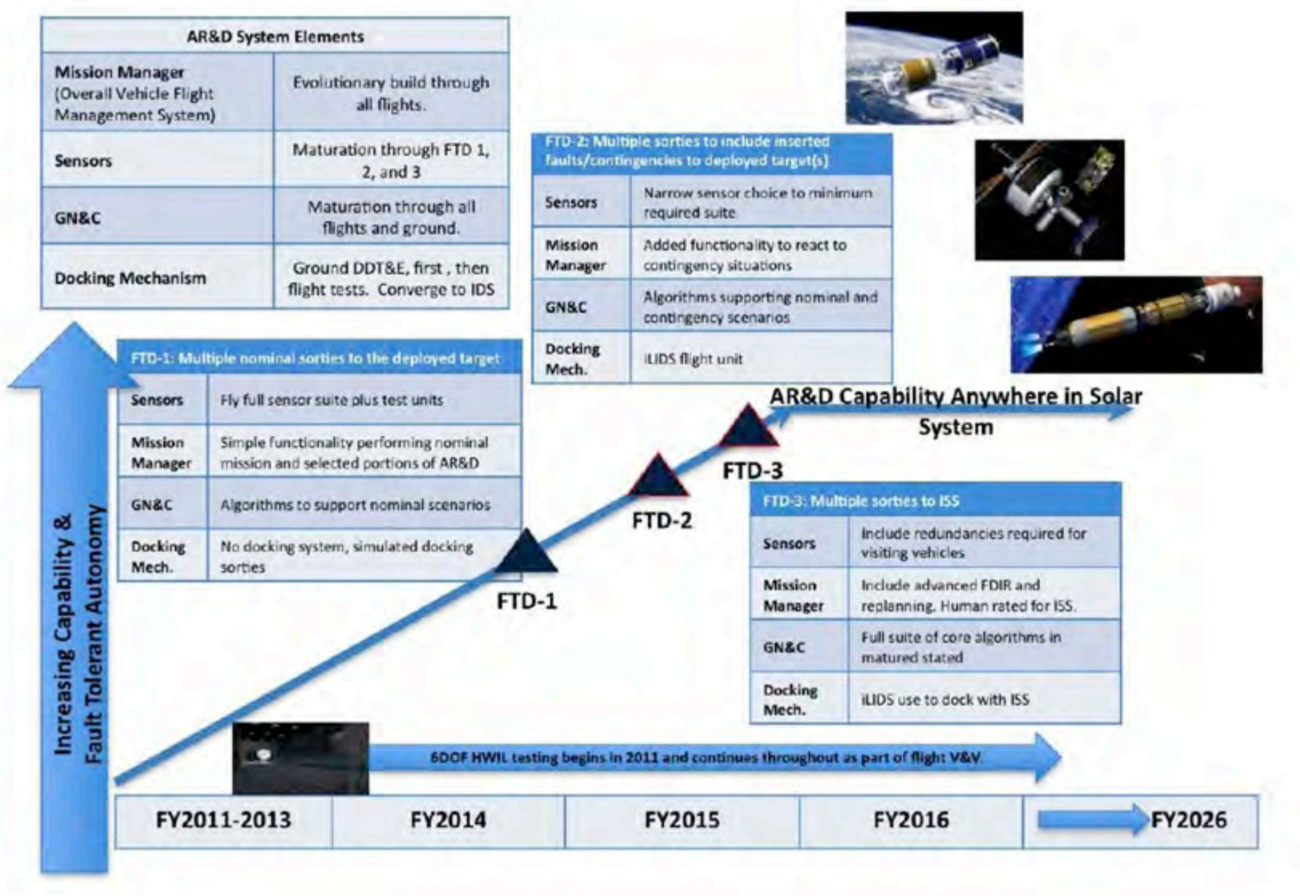

Figure 1: Flagship Technology Demonstration Program Point-of-Departure Mission Campaign

2.0 Cost Models

This section contains the general costing assumptions that were used to initialize a mission-by-mission cost estimate. Each subsection contains information that is used in the more refined analysis to follow unless specifically noted otherwise.

2.1 Cost Assumptions

The following assumptions were made to formulate the cost models:

1. AR&D is considered a capability needed to meet each mission's requirements. Therefore, launch costs and main spacecraft bus costs are not considered as part of the cost of AR&D development.

2. Each AR&D mission will have its own core GN&C providing flight control, absolute navigation, and standard processing capability.

3. The AR&D integration with any mission will leverage off of the avionics test facilities for the mission it is developed under and will not require dedicated, unique lab support after NRE investments.

4. Each vehicle will require at least one Orion Vision Navigation Sensor (VNS), one radio-frequency ranging (RFR) device, and a natural feature image recognition (NFIR) camera/processor/software module.

5. The cost of an engineering unit is 80% of a flight unit.

6. The cost of a qualification unit is 110% of a flight unit to account for spare parts and breakage.

7. ISS RPOD is generally more demanding than other missions in terms of program integration, performance requirements, and verification.

8. Cost data was not available for docking mechanism Non-Recurring Engineering (NRE) and Recurring Engineering (RE) costs and is not included in this treatment.

2.2 Base AR&D Sensor Cost Model

If it is assumed that the Orion Project did not continue past FY10 in terms of development of the VNS and that any RFR and NFIR capability would have to be borne as part of the AR&D Development Program then the cost to develop a first vehicle flight sensor suite is presented in Table 2. This cost model additionally assumes that the first production of sensors will require a moderate spare policy of 2 engineering units, 1 qualification unit, and 2 flight units for a single string early capability. The NRE in this approach is roughly $17,500k with $7,000k of that attributed to completing the Orion VNS NRE (some of which includes the conversion from 28V to 100V power supply currently under consideration in Orion).

Table 2: AR&D Base Sensor Cost Assumptions

Unit	Flight Unit Cost $k		Initial Qty	Cost Risk	Total Cost $k
	NRE	Per Unit	EDU/Qual/Flight		
VNS	$7,000	$2,000	2/1/2	15%	$18,860
RFR	$5,000	$500	2/1/2	5%	$7,718
NFIR			2/1/2	5%	$7,749
S/W	$1,500	$100			
H/W	$4,000	$300			
Total Initial Buy-In	$17,500	$3,000		$3,197	$34,327

2.3 Personnel Cost Model

Personnel costs are estimated according to the labor required to complete the AR&D component of the FTD POD missions. The labor estimate for AR&D specific, non-sensor procurement elements is provided in Table 3.

Table 3: AR&D Personnel Resource Estimate for FTD POD Campaign (in FTE & WYEs)

Skill Area	FY11	FY12	FY13	FY14	FY15
GN&C					
Guid/targ	2.5	1.5	1	1	1
Nav	2.5	2	2	1	2
Control	1.5	1	1	1	1
Mission Manager	5	4	3	2	2
FSW	3	2	2	2	2
Testing	5	4	3	3	3
Integration	3	3	3	3	3
PM/SEI	2	2	2	2	2
FDIR	2	3	1	1	1
SR&QA	2	2	2	2	2
Performance	3	2	2	2	2
Total	31.5	26.5	22	20	21

The assumed rate of this labor is $250k per year and no distinction is made between civil servant and contractor labor.

Table 4: AR&D Personnel Costs for FTD POD Campaign in $k

Skill Area	FY11	FY12	FY13	FY14	FY15	
GN&C						
Guid/targ	$625	$375	$250	$250	$250	
Nav	$625	$500	$500	$250	$500	
Control	$375	$250	$250	$250	$250	
Mission Manager	$1,250	$1,000	$750	$500	$500	
FSW	$750	$500	$500	$500	$500	
Testing	$1,250	$1,000	$750	$750	$750	
Integration	$750	$750	$750	$750	$750	
PM/SEI	$500	$500	$500	$500	$500	
FDIR	$500	$750	$250	$250	$250	
SR&QA	$500	$500	$500	$500	$500	
Performance	$750	$500	$500	$500	$500	
						Totals
Yearly Total	$7,875	$6,625	$5,500	$5,000	$5,250	$30,250
Inflation adjusted to 2010 dollars	$8,111	$7,023	$5,995	$5,600	$6,038	$32,766

3.0 Cost for AR&D through a Multi-Mission Campaign

The detailed cost estimate was developed by beginning with the information from the previous section and then assembling a campaign of combined FTD, ISS servicing, and post-FTD science missions to evaluate how re-use of spares, utilization of expertise, and estimated cost reduction of hardware through a steady supply chain might impact both the overall program cost and the eventual steady-state cost of adding AR&D functionality to both robotic and crewed vehicles. Table 5 lists a campaign of 6 missions beginning with a single string (for relative navigation sensors that indicates one VNS, one RFR, and one NFIR system on the flight vehicle) used to drive out the bulk of the required NRE. Following that, additional missions of the same class, an initial ISS mission, recurring ISS mission, and a projected enhanced mission are each explored for cost effectiveness.

Table 5: Cost Development Mission Campaign

Mission #	Schedule	Flight Year	Summary
1	4 years	2014	First Single String AR&D + NRE, Bears the cost of campaign NRE
2	3 years	2015	Additional Dual String AR&D, Leverages EDUs from Mission 1
3	3 years	2015	First Mission to ISS, After Mission 2, Additional integration with ISS
4	2 years	2016	Recurring Single String AR&D, Steady state AR&D cost for non ISS
5	4 years	2017	Recurring Single String AR&D, Mission Specific NRE, Destination specific mods
6	2 years	2016	Recurring Mission to ISS, After Mission 3, Steady state AR&D cost for ISS

3.1 Mission 1: First Single String AR&D + NRE

The first mission is assumed to be a science or demonstrator mission with an AR&D maturation component. For example, the AR&D activities could be carried out as a secondary objective of the FTD-1 SEP mission. As the first in the development campaign for AR&D, this mission carries the primary NRE cost for the base AR&D software development (GN&C and Mission Manager), FSW implementation, testing, integration, and programmatic support.

Mission 1 also makes the assumptions summarized in Table 6. The reserve is set at 30% to capture the uncertainty and unknowns that always accompany a first integration effort. Similarly, a 130% multiplier is applied to the sensor procurements to reflect supply chain and hardware integration anomalies. Note that the reserve is conservatively taken with respect to the inflated sensor cost multiplier. The total estimate for this mission is $66,000k of which approximately $35,000k is procurement of sensors to establish flight units for this mission and spares for use in the subsequent missions. Details of the Mission 1 cost estimate are provided in Table 7.

Table 6: Mission 1 Specific Assumptions

Reserve 30%
Sensor Cost Scale 130% Assumes more than one primary sensor for testing
One Qual unit per sensor box
Two flight units purchased, one spare
Four year turnaround from ATP
Personnel reflect development, testing with bus system, and integration support with bus system
Significant mission manager and FSW integration work assumed (5 work-years)

Table 7: Mission 1: Single String, Single Mission + NRE (Cost in $k)

Cost Element	Year					
	FY11	FY12	FY13	FY14	FY15	Total
Sensors	$17,500	$6,032	$4,147	$7,540	$0	$35,219
NRE	$17,500	$0	$0	$0	$0	
FTD1	$0	$6,032	$4,147	$7,540	$0	
FTD2	$0	$0	$0	$0	$0	
FTD3	$0	$0	$0	$0	$0	
Personnel	$4,000	$3,750	$3,000	$2,500	$0	$13,250
FTE	16	15	12	10	0	
WYE	16	15	12	10	0	
WYE Cost	$4,000	$3,750	$3,000	$2,500	$0	
Lab Equipment	$1,000	$500	$500	$0	$0	$2,000
Subtotal	$22,500	$10,282	$7,647	$10,040	$0	$50,469
Reserve	$6,750	$3,085	$2,294	$3,012	$0	$15,141
Total	$29,250	$13,367	$9,941	$13,052	$0	$65,610

3.2 Mission 2: Additional Dual String AR&D

Mission 2 models the cost of a follow-on science or demonstrator mission, again with AR&D as a secondary objective. For example, the AR&D capability could be included as part of FTD-2 Advanced Prop Storage/Transfer. Several key assumptions are summarized in Table 8 that modify the cost of mission 2. The reserve is reduced to 15% to reflect maturity from the system integration in mission 1 and a modest economy of scale is assumed in the sensor procurement as the numbers of sensors purchased begin to reflect the fact that production lines are now in place. No EDUs are purchased for this flight as those from mission 1 are re-used. Two flight units are included for sensors to reflect a dual-string reliability approach in the maturing system. No NRE is assumed in this mission as a large investment in the overall AR&D approach was made in mission 1.

The immediate benefits of a development program as opposed to disconnected mission execution are evident in the total cost of AR&D for this dual string mission being $50,000k less than the single string precursor with a total estimated cost of $15,000k of which the majority is used for 3 flight quality sensors ($7,000k out of the total $9,500k sensor budget). The labor cost is reduced considerably to reflect the fact that the base AR&D software and integration costs were paid in the previous mission.

Table 8: Mission 2 Specific Assumptions

Reserve 15%
Sensor Cost Scale 80%
EDUs used from previous mission
One Qual unit per sensor box
Three flight units purchased, one spare
Three year turnaround from ATP
Leverages off of previous missions, so no NRE

Table 9: Mission 2: Additional Mission, Single String, No NRE (Cost in $k)

Cost Element	Year					
	FY11	FY12	FY13	FY14	FY15	Total
Sensors	$0	$0	$0	$2,552	$6,960	$9,512
NRE	$0	$0	$0	$0	$0	
FTD1	$0	$0	$0	$0	$0	
FTD2	$0	$0	$0	$2,552	$6,960	
FTD3	$0	$0	$0	$0	$0	
Personnel	$0	$0	$1,000	$1,000	$1,000	$3,000
FTE	0	0	4	4	4	
WYE	0	0	4	4	4	
WYE Cost	$0	$0	$1,000	$1,000	$1,000	
Lab Equipment	$0	$0	$250	$250	$250	$750
Subtotal	$0	$0	$1,250	$3,802	$8,210	$13,262
Reserve	$0	$0	$188	$570	$1,232	$1,989
Total	$0	$0	$1,438	$4,372	$9,442	$15,251

3.3 Mission 3: First Mission to ISS, After Mission 2

Mission 3 is costed as an AR&D system on a robotic ISS servicing/delivery mission. This could perhaps be FTD-3 Inflatable Habitation module delivery to ISS. The mission specific assumptions are listed in Table 10. The mission reserve and sensor cost scales are slightly higher than in mission 2 in order to represent that the sophistication of the ISS delivery mission and a potentially earlier procurement date than in mission 2 are likely. However, no spare flight units are purchased as they are assumed available from the spares of either mission 1 or 2.

No NRE is assumed for this mission, but the labor is significantly higher than in Mission 2 to account for the fact that integration with the ISS Program and satisfaction of human spaceflight rigor must be addressed in this mission. Leveraging off of the investments in the first two missions, the total AR&D cost (detailed in Table 11) for the first mission to ISS is reduced to approximately $20,000k of which $11,000k is sensor hardware. Again, the advantages of a development program are apparent in the fact that the significantly more complex ISS AR&D mission is executed for only $4,000k more than its preceding robotic mission 2.

Table 10: Mission 3 Specific Assumptions

Reserve 20%
Sensor Cost Scale 100%
EDUs used from previous mission
One Qual unit per sensor box
Two flight units purchased, spares from previous missions
Two year turnaround from ATP
Leverages off of previous missions, so no NRE
Personnel costs to reflect additional testing and interface support to multiple ISS panels

Table 11: Mission 3: First Mission to ISS (Cost in $k)

Cost Element	Year					
	FY11	FY12	FY13	FY14	FY15	Total
Sensors	$0	$0	$2,320	$3,190	$5,800	$11,310
NRE	$0	$0	$0	$0	$0	
FTD1	$0	$0	$0	$0	$0	
FTD2	$0	$0	$2,320	$3,190	$5,800	
FTD3	$0	$0	$0	$0	$0	
Personnel	$0	$0	$1,500	$1,500	$1,500	$4,500
FTE	0	0	8	8	8	
WYE	0	0	6	6	6	
WYE Cost	$0	$0	$1,500	$1,500	$1,500	
Lab Equipment	$0	$0	$250	$250	$250	$750
Subtotal	$0	$0	$4,070	$4,940	$7,550	$16,560
Reserve	$0	$0	$814	$988	$1,510	$3,312
Total	$0	$0	$4,884	$5,928	$9,060	$19,872

3.4 Mission 4: Recurring Single String AR&D

Mission 4 returns to the programmatic roots of mission 1 by supposing an AR&D system is needed for a class B or C robotic mission where single string sensor functionality would be acceptable. Specific assumptions are listed in Table 12 where the reserve and sensor cost scales have both been modified to represent the maturity in the integrated AR&D system, the supporting personnel, and the efficiencies of a now steady production line of sensor hardware. The net result is that the mission cost estimate in Table 13 is $6,600k of which nearly two thirds are sensor hardware cost. This may be assumed to be the steady state single string AR&D system cost. The comparable dual string system would merely add the cost of a flight sensor (one of each type) for an additional $2,610k (a total cost of $9,200k for a dual string system).

Table 12: Mission 4 Specific Assumptions

Reserve 10%
Sensor Cost Scale 60%
EDU's used from previous flight
One Qual unit per sensor box
One flight unit purchased, spares from previous flight
Two year turnaround from ATP

Table 13: Mission 4: Recurring Mission, Single String, No NRE (Cost in $k)

Cost Element	Year					
	FY15	FY16	FY18	FY19	FY20	Total
Sensors	$1,914	$2,610	$0	$0	$0	$4,524
NRE	$0	$0	$0	$0	$0	
EDU	$0	$0	$0	$0	$0	
Qual Unit	$1,914	$0	$0	$0	$0	
Flight Unit	$0	$2,610	$0	$0	$0	
Personnel	$500	$500	$0	$0	$0	$1,000
FTE	3	3	0	0	0	
WYE	2	2	0	0	0	
WYE Cost	$500	$500	$0	$0	$0	
Lab Equipment	$250	$250	$0	$0	$0	$500
Subtotal	$2,664	$3,360	$0	$0	$0	$6,024
Reserve	$266	$336	$0	$0	$0	$602
Total	$2,930	$3,696	$0	$0	$0	$6,626

3.5 Mission 5: Recurring Single String AR&D, Limited Mission Specific NRE

Mission 5 represents a scenario where a new set of requirements emerge that necessitate mission specific NRE to be invested in sensors and personnel. For example, the design for missions 1-4 may have been capable for LEO and lunar missions but perhaps mission 5 adds the demands of a Jovian sample return where extended ranges of operation or environmental shielding must be added to the sensor hardware and new trajectory techniques must be developed for the GN&C software. The assumptions for this mission are listed in Table 14 where it can be seen that the reserve is still low to capture the overall maturity of the integrated AR&D system with 4 missions to its credit but the sensor cost scale has been increased to reflect the fact that these sensors are a modification from the supply line used previously. Similarly, new EDUs and flight spares are needed for the relative navigation sensors as the existing stockpile might not be applicable to this mission.

The effect of not leveraging off of previous hardware purchases in the development and spare strategy is readily seen in the increased sensor and total cost of $29,000k provided in Table 15. Note that $10,000k was assumed to be mission specific NRE which indicates that approximately $12,000k of the total cost is the impact of not using the existing stockpile of equipment, supporting additional personnel, and including additional lab equipment.

Table 14: Mission 5 Specific Assumptions

Reserve 10%
Sensor Cost Scale 90%
New EDU's needed
One Qual unit per sensor box
Two flight units purchased, one as spare
Two years for NRE and new EDU spin

Table 15: Mission 5: Recurring Mission, Single String, Limited Mission Specific NRE (Cost in $k)

Cost Element	Year					
	FY14	FY15	FY16	FY17	FY18	Total
Sensors	$10,000	$0	$2,871	$7,830	$0	$20,701
NRE	$10,000	$0	$0	$0	$0	
EDU	$0	$0	$0	$0	$0	
Qual Unit	$0	$0	$2,871	$0	$0	
Flight Unit	$0	$0	$0	$7,830	$0	
Personnel	$1,000	$1,000	$1,000	$1,000	$0	$4,000
FTE	4	4	4	4	0	
WYE	4	4	4	4	0	
WYE Cost	$1,000	$1,000	$1,000	$1,000	$0	
Lab Equipment	$250	$500	$500	$250	$0	$1,500
Subtotal	$11,250	$1,500	$4,371	$9,080	$0	$26,201
Reserve	$1,125	$150	$437	$908	$0	$2,620
Total	$12,375	$1,650	$4,808	$9,988	$0	$28,821

3.6 Mission 6: Recurring Mission to ISS, After Mission 3

Mission 6 revisits the ISS delivery mission but evaluates the impact of having already executed mission 3 and taking advantage of established interfaces, lessons learned, and hardware stockpiles. The assumptions in Table 16 capture the specific assumptions for this mission. The total cost estimate of $8,400k outlined in Table 17 realizes a cost reduction of $11,000k million from mission 3 and can be assumed to be a conservative mission-to-mission bound for the cost of a proven, dual-string AR&D capability for vehicles visiting ISS.

Table 16: Mission 6 Specific Assumptions

Reserve 10%
Sensor Cost Scale 60%
EDUs from previous missions re-used
One Qual unit per sensor box
Two flight units purchased, spares from previous flight
Two year turnaround from ATP

Table 17: Mission 6: Recurring ISS Mission, No NRE (Cost in $k)

Cost Element	Year					
	FY14	FY15	FY16	FY17	FY18	Total
Sensors	$1,914	$3,480	$0	$0	$0	$5,394
NRE	$0	$0	$0	$0	$0	
EDU	$0	$0	$0	$0	$0	
Qual Unit	$1,914	$0	$0	$0	$0	
Flight Unit	$0	$3,480	$0	$0	$0	
Personnel	$750	$750	$0	$0	$0	$1,500
FTE	3	3	0	0	0	
WYE	3	3	0	0	0	
WYE Cost	$750	$750	$0	$0	$0	
Lab Equipment	$250	$250	$250	$0	$0	$750
Subtotal	$2,914	$4,480	$250	$0	$0	$7,644
Reserve	$291	$448	$25	$0	$0	$764
Total	$3,205	$4,928	$275	$0	$0	$8,408

4.0 Conclusion

The primary purpose of the proposed AR&D Development Program was to highlight the benefits of a coordinated, multi-mission approach to realizing a robust and reliable AR&D capability. The notional mission timeline and budget expenditures have been summarized in Table 18 to give a sample of what the 8 year financial commitment would be from the Agency. The development program would peak in years 3 and 4, as for a brief time 5 of the 6 missions would be in various phases of development. After year 4, the steady state commitment would be less than $10,000k a year to finish the AR&D component of the final 3 missions. The overall program cost would be approximately $142,000k including reserves for an average AR&D cost of $23,600k per mission.

A comparison of missions 4 and 1 (single string) and missions 6 and 3 (ISS) illustrate that the impact of a continuous, Agency-wide, multi-mission AR&D development program can save between $10,000k and $50,000k per mission by leveraging off of mature integrated systems (less reserve needed), a steady production line of standard hardware (reduced per unit costs), and commonality with previous missions (parts stockpiles and a knowledgeable development team). The execution of a program of this scope and focus would potentially reduce the single mission cost of employing a mature and reliable AR&D system to be between $6,000k and $9,000k per mission depending on destination and required redundancy (main impact realized through redundant sensor hardware procurement).

Table 18: Cost Model Program Cost (in $k)

	Year								Mission Totals
Mission	FY11	FY12	FY13	FY14	FY15	FY16	FY16	FY17	
Mission 1: Single String, Single Mission + NRE	$13,367	$9,941	$13,052	$0	$0	$0	$0	$0	$65,610
Mission 2: Additional Mission, Dual String, No NRE	$0	$1,438	$4,372	$9,442	$0	$0	$0	$0	$15,251
Mission 3: First Mission to ISS	$0	$2,100	$5,928	$9,060	$0	$0	$0	$0	$17,088
Mission 4: Recurring Mission, Single String, No NRE	$0	$0	$0	$2,930	$3,696	$0	$3,696	$0	$6,626
Mission 5: Recurring Mission, Single String, Limited Mission Specific NRE	$0	$0	$12,375	$1,650	$4,808	$9,988	$4,808	$9,988	$28,821
Mission 6: Recurring ISS Mission, No NRE	$0	$0	$3,205	$4,928	$275	$0	$275	$0	$8,408
Yearly Total	$13,367	$13,479	$38,933	$28,010	$8,779	$9,988	$8,779	$9,988	Program Total $141,805

References

[1] Mike Conley. Request for Information Synopsis for the Flagship Technology Demonstrations. NASA Solicitation NNH10ZTT003L, http://nspires.nasaprs.com/, May 2010.

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Appendix B - AR&D Business Case Cost Expansion and Applicable Experiences

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NASA Johnson Space Center
EG - Aeroscience and Flight Mechanics
Internal Memorandum

Date: **December 5, 2011** **Document Number: EG-DIV-11-068**

Subject: AR&D Business Case Cost Expansion and Applicable Experiences

The purpose of this memorandum is to expand on the benefits of a proposed campaign approach to development of steady state Automated/Autonomous Rendezvous and Docking (AR&D) capability as outlined in EG-DIV–10-022 "Business Case for a Campaign of NASA AR&D Development". Further examples of the cost benefit of pursuing a strategic, supply-chain oriented AR&D capability and updates to assumptions based on recent practical experiences are presented.

This document is intended as a compliment of EG-DIV-10-022 and represents refinement in thinking and incorporation of inputs from the NASA AR&D Community of Practice since the time of the original campaign development memorandum.

The information contained herein includes or refers to cost estimates and assumptions that are gathered from both ongoing and previous NASA projects and should be considered sensitive in nature.

Prepared by:

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1.0 Case Studies of Steady-State AR&D Costs Per Vehicle

Three mission classes are considered to contrast the potential benefits of an integrated Agency strategy for AR&D development against single-point, project unique designs:

- LEO to non-ISS (e.g. satellite servicing, on-orbit assembly)
- LEO to ISS (dual string, human rated)
- Beyond LEO

1.1 LEO to non-ISS (e.g. satellite servicing, on-orbit assembly)

Following the assumptions in Crain [1], the cost of developing and deploying the AR&D system for a single string single mission with a 4 year development cycle is estimated as $65,610k. For a single mission such as this it is assumed that there is no supply chain so all sensors and algorithms bear the burden of NRE ($17,500k), cost risk ($15,141), qualification units ($3,100k), and flight spares ($3,900k). The total cost of these assumptions is approximately $40,000 or two thirds of the total AR&D cost. Additionally, there is an assumed $13,250 in labor costs associated with not only the systems engineering of integrating AR&D capability into the host vehicle, but also with vetting a one-off system. See Section 2 and Subsection 3.1 in Crain [1] for the details on these costs.

By comparison, if the NRE is retired, supply chain sensors are available with spares from previous flights, algorithms from previous flights are used, and portions of the AR&D system are already vetted then the steady state per mission cost reduces to $6,626 for the same mission and the development time is reduced to 2 years per Subsection 3.1 in Crain [1].

1.2 LEO to ISS (dual string, human rated)

A similar comparison to a mission to ISS must be more carefully calculated because the campaign approach in Crain [1] assumes leveraging off of a single string non-ISS mission as above and an intermediate dual-string non- ISS mission. Again, if the ISS AR&D system is developed independent of supply chain benefits or previous mission parts, experience, and infrastructure then a significant risk, NRE, and first-time integration testing burden must be born by the project. A conservative list of assumptions for such a mission is provided in Table 1 with a resulting cost roll-up projection in Table 2. The total under this assumption set is a staggering $83,369k for a single mission. Note this cost does not assume that a previous space demonstration of components has been flown. If not, then the cost is probably optimistic. If so, then the cost risk may be reduced for the sensors only as the system integration challenges are still present.

However, if investments were made in two previous missions where the NRE and risk are retired, some flight spares are available in stockpile, and a supply chain cost benefit is assumed then the first mission may require as little as $20,000k for AR&D capability (see Crain [1] Subsection 3.3) for the occasional mission and $8,408k for recurring, multiple flights per year missions (see Crain [1] Subsection 3.6). Additionally, if a subsequent BEO mission were flown with similar capabilities, the NRE and spares stockpile reductions could see the campaign development approach steady- state costs for AR&D development on such a mission reduced to as low as $10,000k.

Table 1: First Mission to ISS (one-off approach) Assumptions

Reserve 30%
Sensor Cost Scale 130% Assumes more than one primary sensor for testing
One Qual unit per sensor box
Two flight units purchased, one spare
Five year turnaround from ATP
Personnel reflect development, testing with bus system, and integration support with bus system
Significant mission manager and FSW integration work assumed (5 work-years)

Table 2: First Mission to ISS (one-off approach)

Cost Element	Year					
	FY11	FY12	FY13	FY14	FY15	Total
Sensors	$17,500	$12,452	$12,452	$6,226	$0	$48,630
NRE	$17,500	$0	$0	$0	$0	
FTD1	$0	$12,452	$12,452	$6,226	$0	
FTD2	$0	$0	$0	$0	$0	
FTD3	$0	$0	$0	$0	$0	
Personnel	$4,000	$3,750	$3,000	$2,500	$1,500	$14,750
FTE	16	15	12	10	8	
WYE	16	15	12	10	6	
WYE Cost	$4,000	$3,750	$3,000	$2,500	$1,500	
Lab Equipment	$0	$0	$250	$250	$250	$750
Subtotal	$21,500	$16,202	$15,702	$8,976	$1,750	$64,130
Reserve	$6,450	$4,861	$4,711	$2,693	$525	$19,239
Total	$27,950	$21,063	$20,413	$11,669	$2,275	$83,369

1.3 Beyond LEO

This mission is effectively similar to the single string AR&D mission above but with more stringent sensor perfor- mance and risk tolerance assumptions. A modification of the cost values in Crain [1] lead to a single-mission assumed cost of $56,169k for AR&D capability as illustrated in Table 3. By comparison, if this mission were conducted after a campaign of LEO single string and ISS missions then the steady state cost of such a mission could be as little as $28,821k. That's a significant reduction in cost (50%) but not as great as in the two case studies above. One might wonder why less benefit is realized in this case. The answer is that the BEO mission in the campaign development approach still assumed that a new sensor performance metric was required above and beyond that demonstrated in previous LEO missions. Therefore, NRE was required and flight spares needed for the new sensor capabilities even though the software and techniques of much of the AR&D capability had previously been vetted in the development campaign (see Crain [1] Subsection 3.5).

Table 3: Mission 5: BEO Mission with Full AR&D NRE Burden

Cost Element	Year					
	FY14	FY15	FY16	FY17	FY18	Total
Sensors	$17,000	$0	$4,147	$11,310	$0	$32,457
NRE	$17,000	$0	$0	$0	$0	
EDU	$0	$0	$0	$0	$0	
Qual Unit	$0	$0	$4,147	$0	$0	
Flight Unit	$0	$0	$0	$11,310	$0	
Personnel	$2,500	$2,500	$2,000	$1,500	$0	$8,500
FTE	10	10	8	6	0	
WYE	10	10	8	6	0	
WYE Cost	$2,500	$2,500	$2,000	$1,500	$0	
Lab Equipment	$1,000	$500	$500	$250	$0	$2,250
Subtotal	$20,500	$3,000	$6,647	$13,060	$0	$43,207
Reserve	$6,150	$900	$1,994	$3,918	$0	$12,962
Total	$26,650	$3,900	$8,641	$16,978	$0	$56,169

2.0 Additional Insight Gained Since 2010

2.1 Practical Experience Informing the AR&D Development Campaign Approach

The original business case memorandum assumed that NRE, infrastructure, and risk-reduction could be reduced strategically by coordinating AR&D and AR&D benefitting technology deployments and establishing a supply chain infrastructure. The author is personally aware that claims of high re-use are often overstated at worst or can prove elusive. However, the recent efforts by the Morpheus Project [2] and a technology risk reduction undertaken by the SAFARE proposal team [3] have reinforced that such benefits are very much realizable.

The Morpheus Project indicated that by leveraging the Core Flight Software (CFS) suite from Goddard Space Flight Center (GSFC), the Integrated Test and Integration System (ITOS), and the Trick Simulation environment that approximately 88% of a total of 952 KSLOC of flight, ground, and simulation/analysis software was re-used. Additionally, the team went from no software base to real-time field tested flight software in 14 months.

The SAFARE risk reduction effort continued the experiment into re-use and took the Morpheus beginning with CFS and managed to port the Cygnus COTS AR&D GN&C software into the CFS framework with complete simulation support in less than three months and for a total cost of approximately 1 EP.

The effect of these practical lessons learned is that AR&D software maturity and re-use, benefit from previous system vetting, and rapid development are realizable goals of the campaign development approach. It is possible that the suggested benefits in [1] may prove to be conservative if such a leveraging approach were applied to AR&D in flight development as well.

2.2 Considerations for Trading Re-use Benefits Versus Restrictions

The concept of building iteratively upon vetted AR&D capability and establishing sensor supply chains has many obvious benefits, but one must also consider the potential downsides to such an approach. After all, if a project is gaining from the NRE and experience of previous missions it is also restricted to use those technologies and techniques at the potential expense of newer and more innovative techniques. This subsection seeks to itemize and expand on some themes exploring the trade-offs between complete project flexibility and adherence to an AR&D capability warehouse approach that have emerged in discussions of the NASA AR&D Community of Practice.

2.2.1 Relative Navigation Sensors and Integrated Communications

Advantages of AR&D Development Campaign:

- NRE for multiple projects can be retired early
- Supply chain approach greatly reduces cost and risk over boutique ”one-off” sensor designs
- Flight heritage provides maturity and confidence in components
- Leveraging off of EDU and lab test infrastructure is possible at low to no cost

Restrictions of AR&D Development Campaign:

- Early projects may have to buy more capability than they need if the sensors for the development campaign are more capable than a specific mission requires.
- New projects (such as the BEO AR&D) may have to invest additional NRE to push the performance envelope beyond that of previous missions.

2.2.2 Robust AR&D GN&C & Real-Time Flight Software (FSW)

Advantages of AR&D Development Campaign:

- Software re-use can greatly reduce development and test time as demonstrated by [2] and [3].

Restrictions of AR&D Development Campaign:

- Some in-house software establishments may be resistant to adopting and/or sharing software in an "open-source" fashion within the NASA community.
- Projects will have to abide by some common interface and test standards to keep the FSW suite operational with the addition of new mission capabilities.

2.2.3 Docking/Capture Mechanisms

Advantages of AR&D Development Campaign:

- Of all the systems, this makes the most sense for commonality because it is a hardware interface.
- If new classes of mechanisms are required they can be added to the warehouse of AR&D capability.

Restrictions of AR&D Development Campaign:

- If a new class of mechanism (i.e. small sample return) is required then NRE will have to be expended.
- Some interface and test standards will be levied on each project.

2.2.4 Mission/System Managers for Autonomy/Automation

Advantages of AR&D Development Campaign:

- Autonomous system software needs re-use and shelf-life to wring out flaws, this is provided by the campaign approach
- Missions outside of the AR&D domain can benefit/contribute to this capability. For example, scheduling events during an automated EDL sequence could be done by software very similar to the software that automates AR&D.

Restrictions of AR&D Development Campaign:

- If a new class of mechanism (i.e. small sample return) is required then NRE will have to be expended.
- Some interface and test standards will be levied on each project.

A common concern is also missing innovative new approaches in these areas by abiding by the vetted capabilities in the AR&D warehouse. However, this is a concern that all projects and programs must face as they evaluate the merits of using existing technologies versus seeking out new approaches to meeting their requirements. The AR&D development campaign effort will require some care and feeding therefore to on-ramp new approaches and sunset obsolescent technologies as appropriate to keep the operational, vetted, and rapidly deployable AR&D capability suite continually up to date.

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[2] M. Ondler. Morpheus Vertical Test Bed: A Case Study. Presentation to the NASA Engineering Leadership Workshop, September 2011.

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