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Space Systems Architecture for the Crew Mission Trainer

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NASA needs to prepare astronauts for spaceflight training in nominal and emergency scenarios for missions in the post-Shuttle era. NASA will be retiring Space Shuttle training and operations in concert with the Shuttle retirement by 2010, and the next astronaut class will rehearse in new Constellation training facilities. The strategic plan to move from a winged, reusable space vehicle to an in-line rocket with a crew capsule at the nose has changed the crew flight environment considerably. Relatively benign flight regimes for the crew have now been replaced with scenarios having more extreme flight conditions. Ground launches will have considerable vibrations, shock and accelerations, and capsule re-entry/landings could have sustained load conditions of at least 7 Gs. A review of current Constellation training and operations architecture has indicated a potential gap in coverage for a full-task trainer that simulates the most extreme conditions. In order to support future space vehicle training and operations, a concept was developed for a dynamic three degree of freedom, centrifuge-based crew flight trainer which simulates the full mission environment in all flight phases. For this study, a rigorous systems engineering approach was used to create a fully integrated set of concept of operations, requirements, and an architecture that meets the needs of NASA in the 21st Century. Systems engineering techniques were applied to the architecture, using various analysis methods such as stakeholder interviews, use case diagrams, requirements definition, alternate design trades, and functional flow diagrams. The result of this study was a novel trainer based on commercially available technology that has received attention from NASA mission training/operations engineers as a viable option for anticipated NASA plans regarding Constellation training and operations architecture. This analysis brought into focus the need for a trainer within the overall Constellation architecture that simulates anticipated extreme environments. These environments include sustained positive and negative g-forces, acoustic environment, and vibration with flight-like displays, controls, and crew interfaces that will enable the crew to be prepared for nearly all possible flight scenarios. It was found beneficial to have all types of NASA flight training consolidated into one facility by using the proposed trainer, thus saving training time and cost.

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Nomenclature

AFB	=	Air Force Base
CAD	=	Computer Aided Design
CCT	=	Crew Compartment Trainer
CEV	=	Crew Exploration Vehicle
CM	=	Crew Module
CMT	=	Crew Mission Trainer
DOF	=	Degree of Freedom
ED	=	Experience Design
HVAC	=	Heating, Ventilation and Air Conditioning
IDEF0	=	Integrated Definition for Function Modeling
ISS	=	International Space Station
JSC	=	Johnson Space Center
NASA	=	National Aeronautics and Space Administration
SE	=	System Engineering
SMBS	=	Shuttle Motion Base Simulator
SSP	=	Space Shuttle Program
WBS	=	Work Breakdown Structure

I. Introduction

The vision of the National Aeronautics and Space Administration (NASA) is to explore the Moon, Mars and beyond. To fulfill this vision, NASA has embarked on the development of the Orion vehicle, which will replace the Space Shuttle as the United States' spacecraft to enable human access to space. Upon completion, Orion will be capable of transferring crew and cargo to the International Space Station (ISS), as well as transporting crew to the Moon and beyond. The Crew Exploration Vehicle (CEV) resides within the Orion spacecraft system. The Crew Module (CM) portion of CEV houses the crew during all mission phases, and the astronauts operate the CEV while strapped in seats from launch to entry and landing. Figure 1 shows the basic configuration for CEV which includes the crew capsule or CM during flight operations.

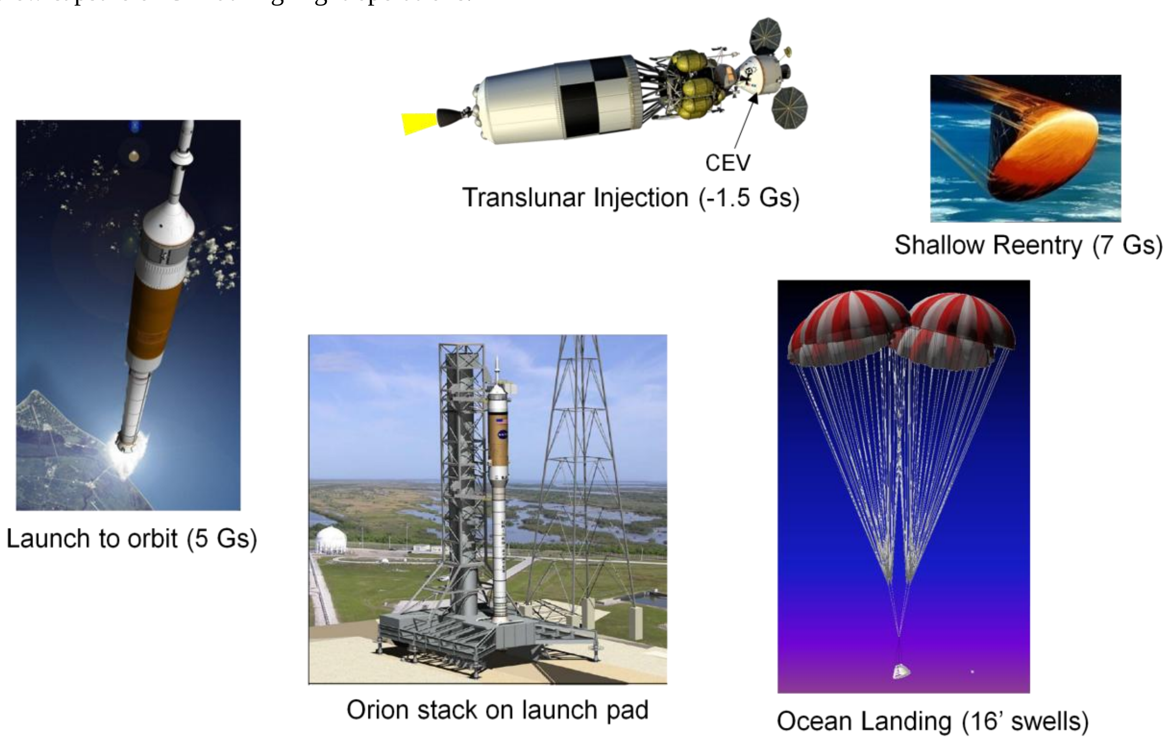

Figure 1. NASA Orion spacecraft architecture and operation concept

To ensure this NASA vision is successful, all the necessary preparation for crew spacecraft training must be made in advance. Personnel (i.e., trainers and the astronaut crew) are needed to operate this machine once CEV is built. In order to successfully complete a mission, the users must fully understand the vehicle that is being controlled. To prepare the crew, the environments that the astronauts are expected to experience must be duplicated for training purposes. The adage: 'Practice makes perfect,' is directly applicable in this case. By knowing exactly what to expect, and how to react, the training and knowledge of the crew significantly increases the probability of a successful mission significantly. In addition, NASA has repeatedly used the more realistic training simulators to help solve real-time operational problems during missions when a crisis occurs.

With Orion, relatively benign flight regimes for the crew in the past have now been replaced with scenarios having more severe flight conditions. Ground launches will have considerable vibrations, shock and accelerations, and capsule re-entry/landings could have sustained load conditions of at least 7 Gs. If a ground abort should be necessary, the crew could see up to 12 Gs for a short duration. A review of current Constellation training and operations architecture has indicated a potential gap in coverage for a full-task trainer that simulates the most extreme flight conditions. During this study, one of key findings was that legacy architectures cannot be used due to their limited life-like capabilities.

There are currently no full-task simulators in use by NASA that will meet the needs of training the crew in a realistic environment. NASA therefore needs a crew flight trainer which simulates the full mission environment in all flight phases, including sustained positive and negative G-forces. All displays, controls, and crew interfaces must be flight-like. For purposes of this study, the key capabilities and performance characteristics desired by the stakeholders (those who have a direct or indirect input on the system) require the trainer to:

- Operate in a safe, realistic mission training simulation environment
- Be certified and delivered by January 1, 2015
- Not exceed $40 million cost cap (in 2009 currency)

Various personnel and agencies, along with contractors will play a role in any training system. The active stakeholders within NASA for such a mission training system include: the astronaut crew, the astronaut trainers, facilities, and maintenance personnel. Key expectations are for a safe, easy to use, and realistic training system that integrates with current and planned NASA assets, and is available early enough to support crew and operations personnel training. Passive stakeholders include: regulation agencies (e.g. Federal Government), the public, developers and contractors.

To summarize needs, goals and objectives, the proposed architecture referred to as the Crew Mission Trainer (CMT) will provide an unparalleled training experience with an extremely realistic environment that will significantly change the way NASA trains astronauts. With implementation of this architecture, consolidation of training assets are possible, and a pay-as-you-go approach can be done with associated reduced costs. The hardware will be human rated with built-in safety measures. Finally, the objective of the CMT is to provide a simplistic approach to life-like human spaceflight training. Ease of simulation operability is vital during training because the personnel are focused on preparing for the mission and should not be distracted by complicated software and hardware.

II. Legacy Architecture and System Context

Within the realm of spacecraft flight training, impressive advances have been made since the Apollo era (1960's). Soon after the Apollo program, training simulators were being operated not only by mechanical hardware, but computer software as well. Simulators gained enhanced controls and responses that made the training more life-like since the development and common use of the computer. However, some simulators have reached a high level of fidelity and reflect real world conditions, whereas others intentionally do not. For part-task training, full realism in all areas is usually not necessary.

A. Legacy Architecture

The boundary of the system being conceived is primarily based on the need for a full-task trainer, and consists of several areas of focus. First, it is necessary to understand both the systems that have been used in the past, and the systems that are currently in use. Figure 2 shows two types of simulators: an early multi-axis centrifuge specifically designed for the Mercury space program, and the 25 foot arm Air Force centrifuge at Brooks AFB which is capable of +15 Gs or more.

Mercury Program

Air Force - Brooks

Figure 2. Legacy simulator and training capability

In the past, NASA has relied on a variety of methods for training simulation. As shown in Figure 3, these products consist of multi-axis simulators on moving platforms or with air-bearing floors, projection domes, and even virtual reality. In addition to the moving simulators, NASA has used many stationary trainers for part-task training as well (not shown).

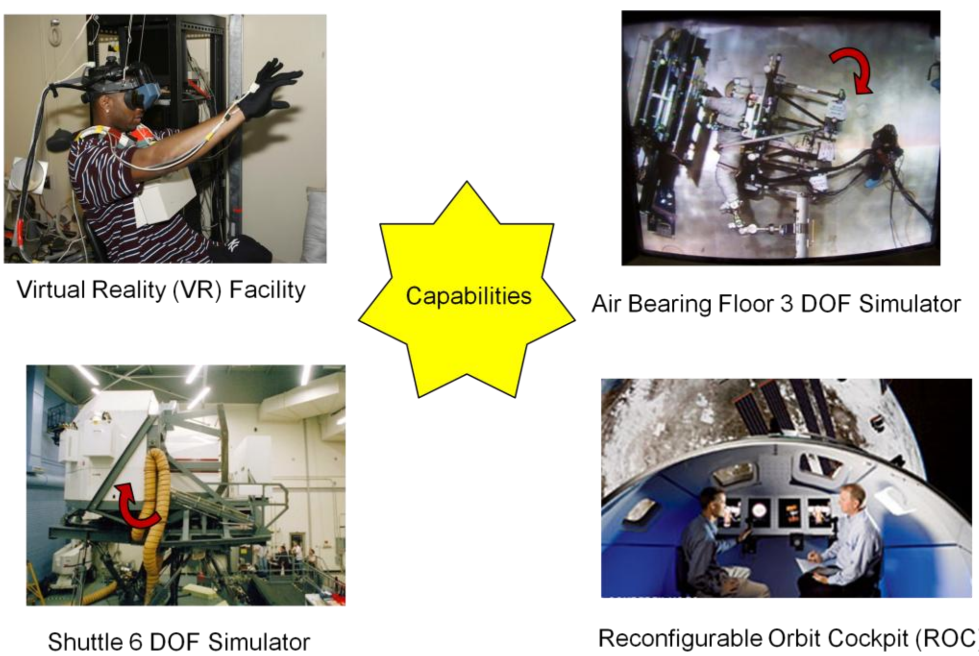

Figure 3. NASA simulator and training capability

B. Initial Reference Architecture

The reference architecture that NASA uses for Shuttle training is a collection of hardware and software systems, as depicted in Figure 4. Typically, the crew will first train in the Crew Compartment Trainer (CCT), located in JSC Building 9. The CCT has the capability to be raised and rotated in 2 positions; vertical for simulated launch, and horizontal for simulated landing configurations.

The flight crew additionally trains in a 6-DOF shuttle simulator in JSC Building 5. The Shuttle Motion Base Simulator (SMBS) is a full-scale replica of the orbiter's flight deck forward station. It sits on a 6-DOF hydraulic platform, enabling a simulation of launch and landing which feature movements (including vibration), noise and a real-time visual display (which represents what the astronauts would see). The SMBS can also pitch up almost 90 degrees to position the crew members on their backs during launch simulations. It has seating for a crew of four: the commander, pilot and two mission specialists. All controls and displays are active, and visual and aural cues are provided. The SMBS provides motion cues essential for an accurate simulation of launch, ascent, de-orbit, entry and landing, does not provide sustained g-forces.

In addition to these ground-based systems, NASA also uses several types of jet aircraft for astronaut training. The aircraft trainers that NASA utilizes includes: the Gulfstream Landing Trainer (which simulates the Shuttle flight control inputs and resulting landing flight path), the T-38 supersonic jet trainers (used for maintaining pilot flying proficiency and reaction skills, and the zero-g simulator (used for astronaut candidate zero-g familiarization flights).

All of these separate hardware systems comprise the astronaut training program, and are very costly to maintain; they are typically not reconfigurable without substantial cost. As a result, it could be stated that the current astronaut training program at NASA does not reflect an applicable set of strategic planning measures for the future.

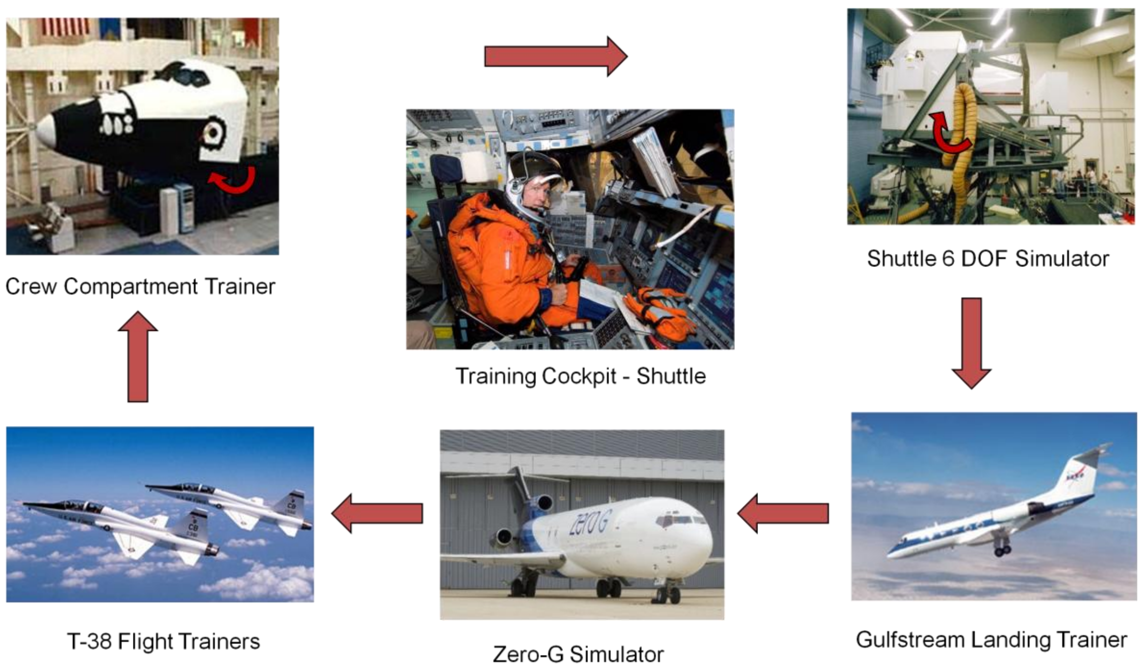

Figure 4. NASA flight training process and resources

C. Commercial Architecture

The commercial ride simulation industry now has advanced to the point where it has overtaken, in some ways, actual spaceflight training methods in terms of realism. In 2003, the Walt Disney Epcot Center Theme Park opened a new ride called Mission: SPACE. Some astronauts regard this ride as very realistic and flight like, since it combines almost the full elements of the space environment. The ride was developed as a multi-arm centrifuge for use at amusement parks. Listed below are some of the facts on this type of ride:

- Developed hardware, with operational experience – 11 million + users to date
- Gondola is sized for 4 users (trainees), strapped in seats
- User roles: Pilot, Commander, Navigator or Engineer
- 2.5 G capable centrifuge (sustained)
- Pitch capability: +45°, -55°
- Roll capability: ± 25°
- Realistic video, audio, and vibration
- Fictional training plan followed on flight to Mars
- Active user participation (activate timed switches)

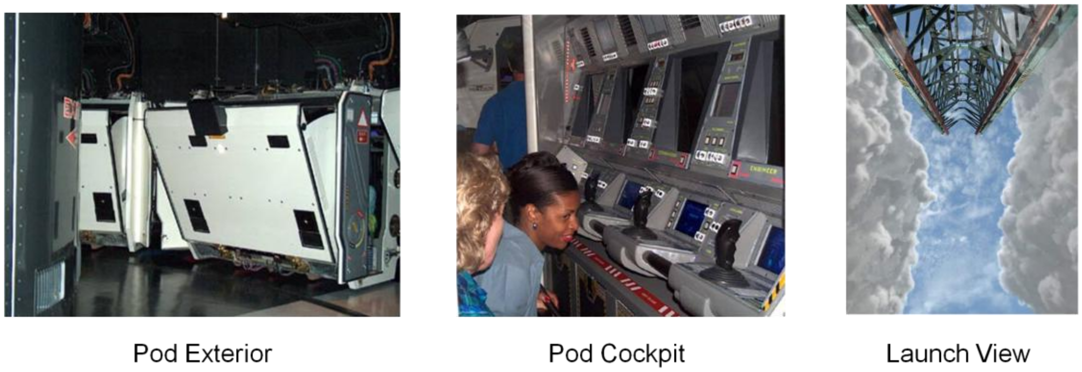

Figure 5. Disney ride simulator, Mission: SPACE

The ride, Mission: SPACE, and others like it have now entered the realm of what is an emerging area of design known as Experience Design (ED); an uncanny, theoretically aware mixture of art, simulation, and psychological mischief-making. It is not actually a field of its own, but a radically different approach to basic design. The intent of ED is marked by its consciousness of every element - emotional, physical, tactile - that surround any given experience, thereby heightening the intensity with which that experience is felt. Ultimately the intent is to reach a level of realism so immersed and intense that you are convinced you *are* in danger.

D. Stakeholder Context Diagram

As with any architecture definition, the most important issue is where to draw the system's boundaries. Within the boundary of the training system, there are active stakeholders and other reference systems that interact with a training simulator. The stakeholders should have a say in boundary definition, but ultimately the 'payer' of the system will have major input as well. Figure 6 depicts this representation for a typical training system for the crew.

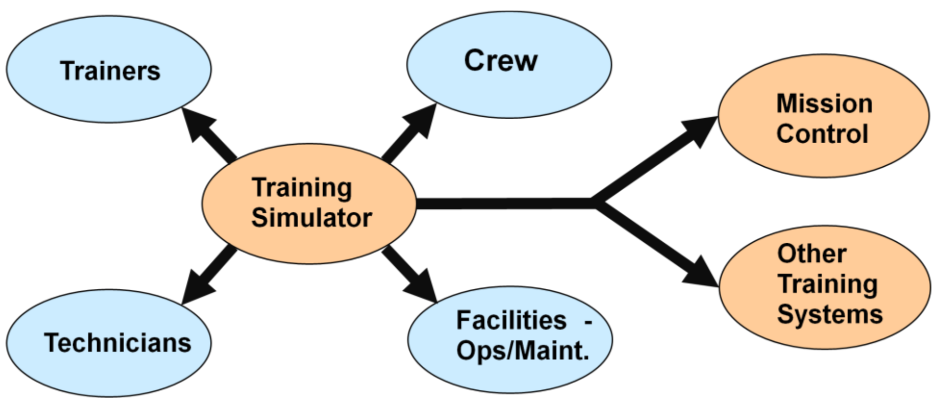

Figure 6. Stakeholder and system context diagram

E. Use Case Diagram

Originally intended for software development, use cases have been proven useful for most types of systems development. A use case is essentially an operational scenario, and in its most basic form, it starts with the key stakeholder or operator/user to generate a number of simple scenarios. Next, scenario generation is expanded to include other stakeholders. Use cases can proceed to further complexity including failure modes, but all scenarios should focus on what the stakeholders and external systems do to the system, and not on how the systems accomplish their tasks. In essence, the system should be viewed as a 'black box', where only the inputs and outputs to the system are declared. Activities follow in a chronological sequence, and are shown from top to bottom in the diagram. The system's inputs and outputs cross the boundary, implicitly generating input/output requirements and external interfaces.

This section introduces an operational scenario that could be used to operate a training simulator, as shown in Figure 7. The two types of operators that are capable of providing input are the trainers and crew members with the 'simulation' itself as the black box. By inputting various pre-programmed variables into the simulation, the operator can create a unique and challenging training scenario each time. The simulation may be controlled both inside the cabin (by the crew), and in the trainer control room. To better express the simulator process, an example of an input/output diagram, or use case was constructed to explore the training needs as provided in Figure 7. For abbreviation, only the initial portion of the scenario is shown. For further information, refer to an AIAA Space 2009 conference paper entitled, "Crew Mission Trainer – A Space Operations Training Solution for the 21st Century" by H. VanAntwerp.

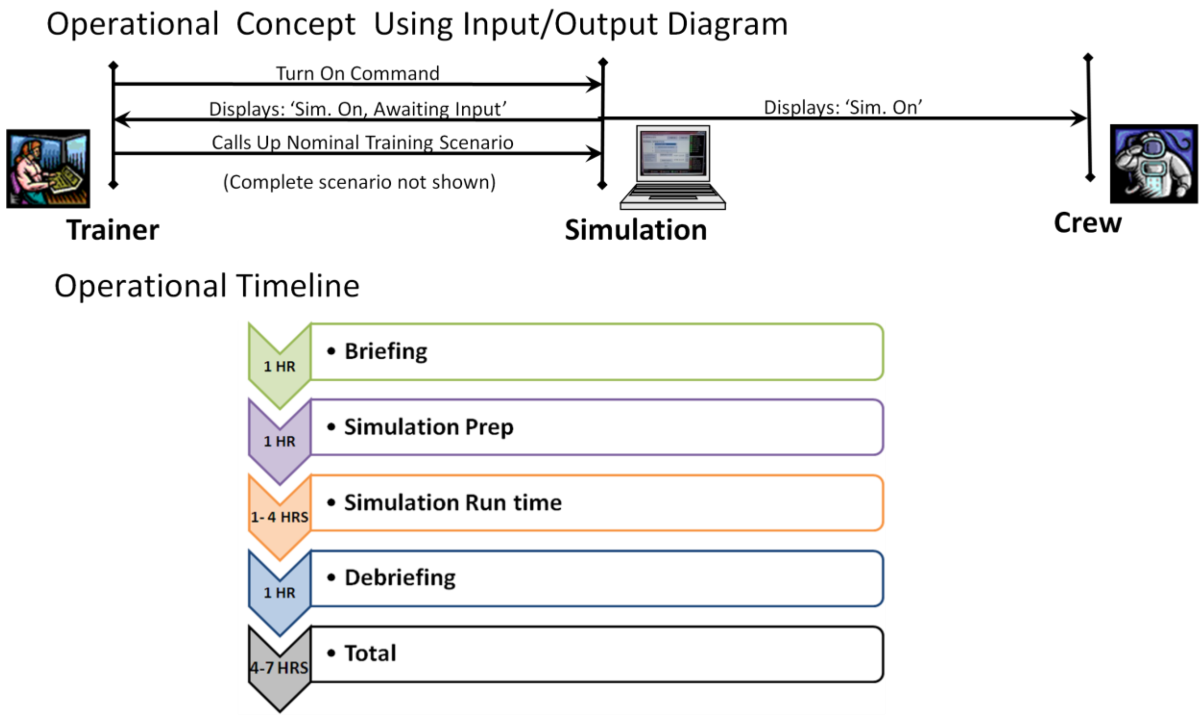

Figure 7. Sample Use Case diagram and operation timeline

For NASA's next generation training simulator system, the intent is to marry the need for a space mission trainer with the latest advances in commercial multi-arm centrifuge technology. Secondly, the proposed hardware will represent a consolidation of training into one unified system. The next sections intend to show exactly how this will be done.

III. System Drivers and Constraints

This section describes the performance drivers and constraints that have a major impact on the success of the project. Definition of these drivers will be important when assessing alternative implementation concepts for the system and its elements in later sections. Constraints to the existing NASA environment that help bound the problem will also be discussed, and they assist in defining the nature and limits of the proposed system. Later, using these system drivers and constraints as pseudo requirements, functional and process models will be used to help define the architecture.

A. Performance Drivers

For a training system to be as realistic as possible, the environment the crew is subjected to should either match the real world parameters, or 'trick' the mind and body to think that it *is* in the actual environment when it is not.
The body physiology has motion sensors which include the vestibular system (ear), muscle-and joint sensors, and sensors that track whole body movements. In addition, the brain is subconsciously accustomed to receiving a motion cue before noticing the associated change in the visual scene. If motion cues are not present to back up the visual, some disorientation (causing "simulator sickness") can result due to the cue-mismatch compared to the real world. This presents an immense challenge. To work within the human experience, training simulators must employ a variety of methods. In addition to supplying the actual instruments, displays and controls, there are visual,

aural and motion cues provided by computer generated out-the-window scenes, hidden speakers, and motion platforms.

Understanding performance drivers are critical to the success criteria and validation of the CMT concept and must be ascertained at several levels. The key to understanding is the fact that the flight environment of the spacecraft has to be mimicked as closely as possible. Crew feedback will be necessary at various development stages of the project to both prevent last minute surprises and to come as close as possible to reality. In addition, a robust system that can vary enough parameters to fine-tune the response is a given to reduce project risk. Another method to validate the flight characteristics is to take advantage of a proof-of-concept early on, in order to demonstrate the future outcome. Commercial facilities exist with which to perform this activity for this trainer concept.

The key flight performance parameters targeted for a lunar CEV mission simulation include:

- Sustained G-forces (+12, -3)
- Sustained pitch and roll rates (360°/sec)
- Vibration and shock levels at critical periods (launch, landing, TLI burn, etc.)
- Video screen & audio output must be high resolution to mimic real scenes
- Thermal environment of up to 110° F
- Suited and unsuited situations

B. Physiological Constraints

Just as in aircraft, the human body in a spacecraft is the limiting factor for maximum allowable loads, rather than the vehicle itself. Accounting for this fact, limits are either placed on how the vehicle responds during its flight path, or the crew is isolated within the vehicle - especially during launch, landing and abort modes.

In order to properly constrain and size the CMT, the human limits within CEV need to be understood. Above all, sustained human physiological limits must not be exceeded for safety reasons. Based on the performance listed in Section B, the centrifuge arm length as a variable versus its revolution motion or speed was studied for various G-force loadings. This yielded a carpet plot as shown in Figure 8. It is interesting to note that a 10 foot long centrifuge arm must rotate 41% faster than a 20 foot long arm when achieving the same G-force. At some point, high rotation speeds cause side effects that must be avoided. This is the primary reason the Brooks Air Force Base (AFB) centrifuge arm is over 20 feet long.

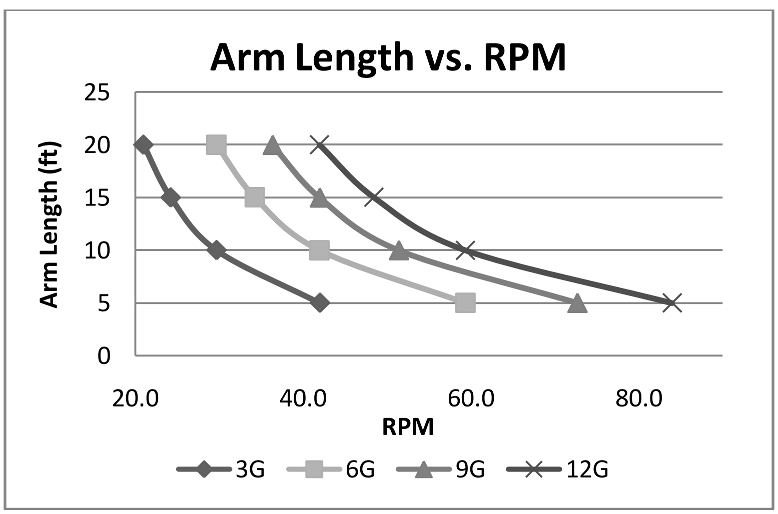

Figure 8. Effect of Centrifuge arm length on RPM

Next, the effects of various G-forces on a selected arm length of 20 feet were studied. Results are shown in Figure 9. This length keeps the overall size of the trainer within the floor constraints of larger, existing NASA buildings, and also maintains rotational speed below 45 rpm (less than one revolution per second).

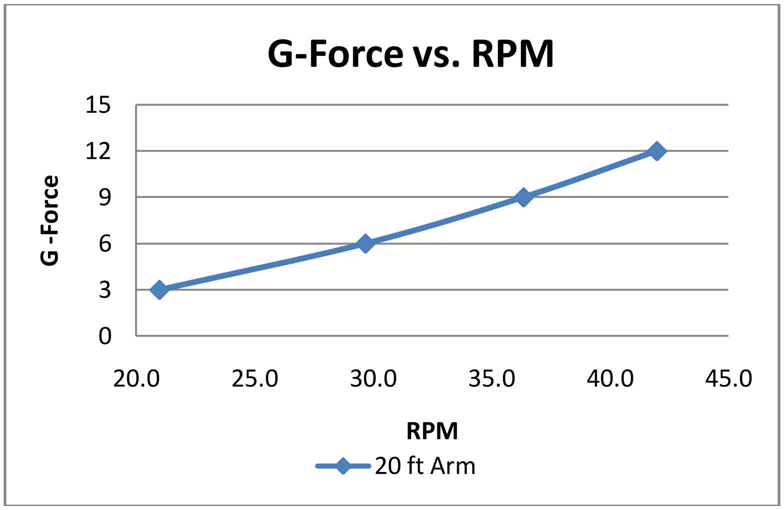

Figure 9. Effect of G-force on RPM (20 ft arm)

During this study, several findings were understood:

G-forces are driven by:

- Centrifuge arm length (feet)
- Tangential speed (feet/sec.) or RPM
- Pitch & yaw rates are limited by human tolerance (360°/sec. or less)
- If the design of the space simulator is compromised, then spatial distortions and artifacts will occur, not matching perceived reality

For short arm lengths:

- Severe gravity gradients occur
- Lateral acceleration to G-level is more noticeable.
- Longer arm length is ideal, approx. 15 - 20 feet for less than 12 Gs. The more length, the better.

C. Facility and Hardware Constraints

Equally important are the constraints that directly influence the design of the simulation trainer, which include:

1. The centrifuge should not exceed 50 feet in diameter, based on +12G, -3G maximum centripetal force for short duration.
2. Overhead height, floor loading, power draw, vibration and dampening into the facility. The system shall also be compatible with the crane system in the selected building.
3. Internal cockpit to be based on released drawings for the Crew Module. Government Furnished Equipment (GFE) will include suits, umbilicals and hookups. Simulation software and graphics will also be supplied as GFE.
4. During training operation, assume that the Crew Impact Attenuation system (CIA) will not be activated (e.g. stroked seats).

D. Infrastructure

The logical location for crew training is at NASA JSC. Many of the facilities at NASA JSC have been previously developed for the Space Shuttle Program (SSP). The SSP will be officially ending in 2010, so there will be considerable shuffling of assets in and out of existing facilities. At the site, there are only a few buildings that have pre-existing infrastructure capable of supporting the flight training and simulation hardware required for full-task training. Each building site must be considered for its capabilities and retrofit potential.

Working within the NASA environment is somewhat unique compared to the Department of Defense and other industries. NASA has a highly trained technical workforce, and prefers a closer involvement with the contractor, even after a project is authorized and requirements are approved. This type of constraint is important to understand when assessing overall project cost and schedule.

As mentioned, these performance drivers and system constraints will be important in selecting a design concept that also meets the customer's needs. The following sections clarify that system architecture. As with any NASA program, there will be cost and schedule constraints. Adhering to these constraints is extremely important, as training capability is needed within a specified time period prior to first flight of the CEV to the ISS or the Moon. Any adjustments in requirements for the project can moderately to severely affect this constraint, depending on the impact.

IV. Implementation Concepts and Rationale

A. Concept Research and Alternate Architectures

In order to optimize the design selection for the CMT architecture, several competing concepts or alternatives were developed. The following concepts, as shown in Figure 10 are:

1. Multi-arm Long Centrifuge
2. 2-DOF Roll Cage
3. Fixed Pod Centrifuge
4. Multi-arm Short Centrifuge
5. 6-DOF Motion Pod

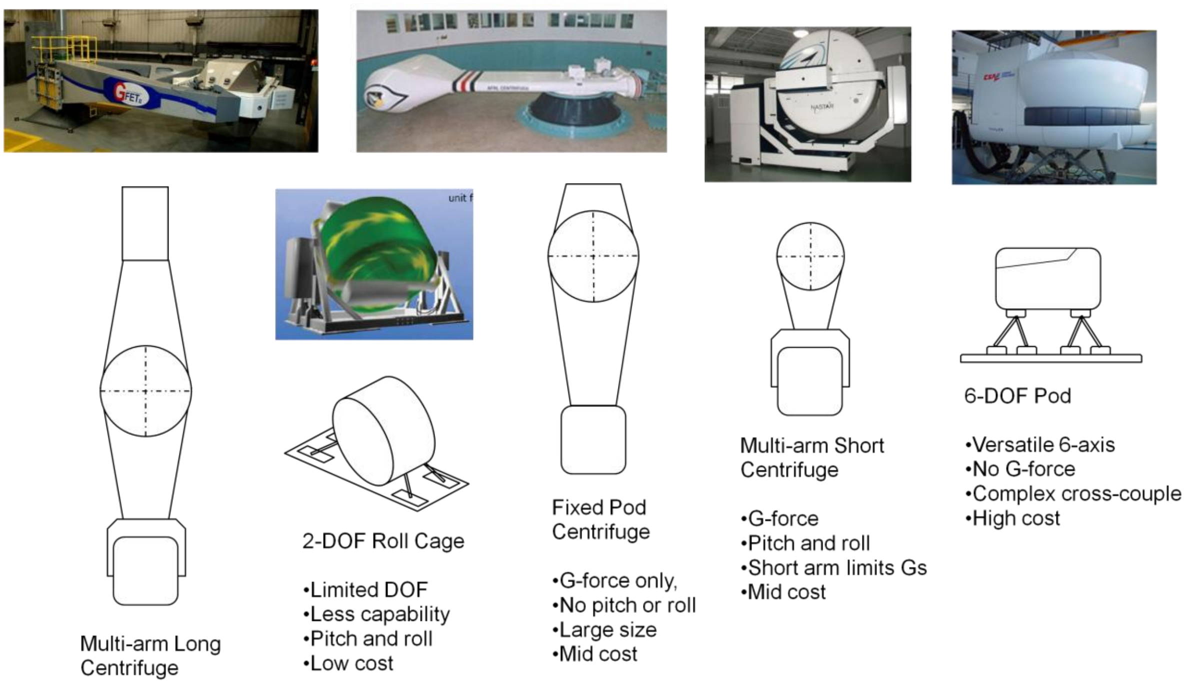

Figure 10. CMT concept alternatives and synthesis

B. CONCEPT TRADE STUDY

For the concept trades, a Pugh matrix (reference 2) was used to assess relative scores between each of the 5 designs. A Pugh matrix is somewhat of a pre-screen method, rather than using an elaborate trade study with criteria and weighting factors. However, it does quickly show the leading contenders which may be of interest from a qualitative standpoint. Results for the CMT study are shown in Table 1 below. In this case, the 2 lowest scores (shown in red, totaling 2 points each) were reviewed and discarded. The 3 most promising candidates were further researched. It is worth noting that when using a Pugh matrix, there is a considerable amount of engineering judgment used, and experience in the domain of system interest is invaluable in the down-selection process.

Table 1. CMT Pugh Matrix rating scores

Pugh Matrix - MMT		Concept 1 Multi-arm long	Concept 2 2-DOF roll cage	Concept 3 Fixed pod	Concept 4 Multi-arm shrt	Concept 5 6-DOF pod
Usability:						
	Maintenance	+	-	+	-	-
	Reliability	+	+	+	+	+
	Safety	+	+	+	-	+
	User Friendly	+	+	-	+	-
Ride Quality						
	Accuracy	+	-	+	+	+
	Realism	+	-	-	-	-
Performance						
	G-Force	+	-	+	+	-
	Response Time	+	-	+	+	+
	Degrees of Freedom	+	-	-	+	+
	Vibration/Shock	+	+	+	+	+
	Thermal Effects	+	+	+	+	+
Operations						
	Size	-	+	-	+	+
	Cost	-	+	-	-	+
	Pwr	-	+	-	+	-
	Σ +	11	8	8	10	9
	Σ -	3	6	6	4	5
	Sum Total	8	2	2	6	4

Concept 5, the 6-DOF pod, is based on a variant of the Shuttle trainer currently used. One of the key parameters it cannot perform is sustained positive and negative G-forces. Concept 4, the Multi-arm Short centrifuge based design, received a total of 6 points in the Pugh Matrix. It is a strong contender for meeting the CMT criteria, since it provides a multi-DOF and sustained G-force environment. However, it has one strong drawback: the crew's physiological affects due to rapid changes in velocity vector. The effect causes spatial distortions to occur, not matching perceived reality. When the vestibular system does not match reality, the response is disorientation and nausea. This key parameter is a driver in selecting the final design, and the only way to resolve this issue is to lengthen the arm.

Concept 1, the Multi-arm Long centrifuge based design, received the highest score in the Pugh Matrix and was chosen as the baseline design. Overall, this concept answers the customer needs and acceptance criteria the best. It can safely provide a multi-DOF capability with sustained positive and negative G-forces. The system has already been developed, is well understood, has had variants fielded for several years (showing an excellent match to perceived reality) and it has a relatively safe record of operation. It is larger and more expensive than most alternatives, but the cost is offset by the planned consolidation of NASA training assets. Since it is based on Commercial off-the -shelf (COTS) technology, development risk is minimized and adherence to a well planned project schedule is more likely to occur.

V. Proposed System Architecture

Previously in the Introduction, a mission description with customer needs and goals was given, and in Section III, system performance drivers and constraints were detailed. Based on this foundation of understanding, a system architecture of elements and sub-elements is now defined for the CMT.

A. External System Diagram

The use of a system diagram is helpful in understanding the external systems that interact with the CMT, and its behavior as an operational architecture. Figure 11 depicts the CMT as a boundary, and looks at the influence of external systems and people as shown. As shown, the external systems can impact the system, and the system also impacts the external systems. However, one exception is the existing system called Mission Operations, which is considered the system's context. In this realm, an external system can impact the system, but not conversely, since it is a legacy system. Note that the arrows define the direction of action between the system and external systems.

At this point, system level requirements can be defined based, on the efforts leading up to maturity in the process and a preliminary design of the architecture. Key requirements can include input/output or functional, performance, safety, and the essential interfaces. Originating requirements by the stakeholders (statements about capabilities) help in defining the constraints and performance parameters within which the system is to be designed, and this is important especially when validating the system later in development.

Figure 11. External system diagram for the CMT

B. Functional Architecture

Rather that start with the physical architecture of a system definition, this study looks at the functional architecture first. This may seem initially awkward, but as will be shown, the data and syntax correspond with the inputs into the process model which is described in Section C. A function (in SE parlance) is a transformation process that changes inputs into outputs. Function syntax utilizes verbs in each of the boxes, rather than nouns, and asks 'what does the element do?' The system is modeled with a single, top-level (system) function that can be decomposed into a hierarchy of sub-functions. Figure 12 depicts the functional architecture tree down to the second level (3 levels). The question naturally arises, 'how far does one go in terms of levels?' The answer is essentially to go down far enough to adequately define the transformations that resolve concerns and risks, and thus it indirectly addresses the level with which to monitor or manage a project.

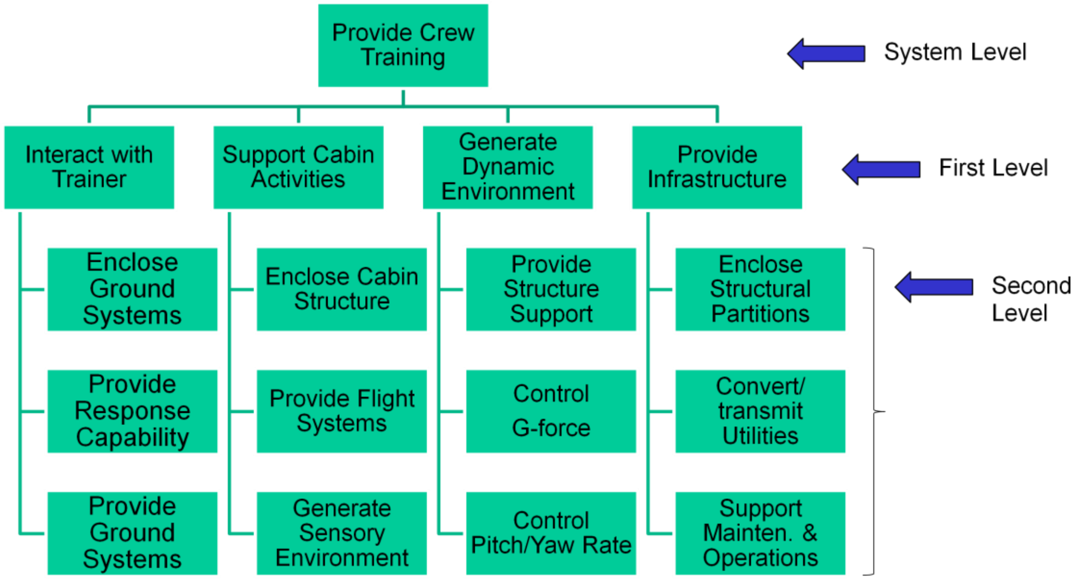

Figure 12. Functional architecture tree for the CMT

C. IDEF0 Model Diagram

Models, which are considered abstractions of reality, are critical in the engineering of systems. There are many ways to analyze a system using process modeling techniques, including data flow diagrams and N2 charts, Function Flow Bock Diagram (FFBD), Quality Functional Deployment (QFD) charts, house of quality, risk based assessments, etc. This study primarily focuses on the use of an IDEF0 methodology for systems analysis. IDEF0 charts were first used by the military in the 1970s. An IDEF0 (Integrated Definition for Function Modeling) is known as a definitive model, because it addresses the question of how an entity or system should be defined. The main focus is on building a definition of how the system is being designed in terms of inputs and outputs, functions, and resources. The IDEF0 model is popular because it uses a standardized set of semantics and syntax that form logical expressions and meanings. It uses a hierarchical method of decomposition that is readily available in software packages for systems engineering such as CORE (reference 6). In the IDEF0 chart, as shown in Figure13, inputs enter into each function box from the left, controls that guide the transformation process enter from the top, mechanisms (physical resources that perform the functions) enter from the bottom, and outputs leave from the right. Flow of material or data is represented by an arrow that connects function boxes. Inputs and controls are often confused; inputs are items that are transformed or consumed in the functional process associated with the production of its outputs, whereas controls are information or instructions that guide the functional process.

Usually, a process model is developed, tested and then refined. The model should also be validated, and checked to see that it is answering the right questions. The boxes in Figure 13 correspond to the functional tree architecture decomposed at the first level, the zero level referring to the CMT as the system.

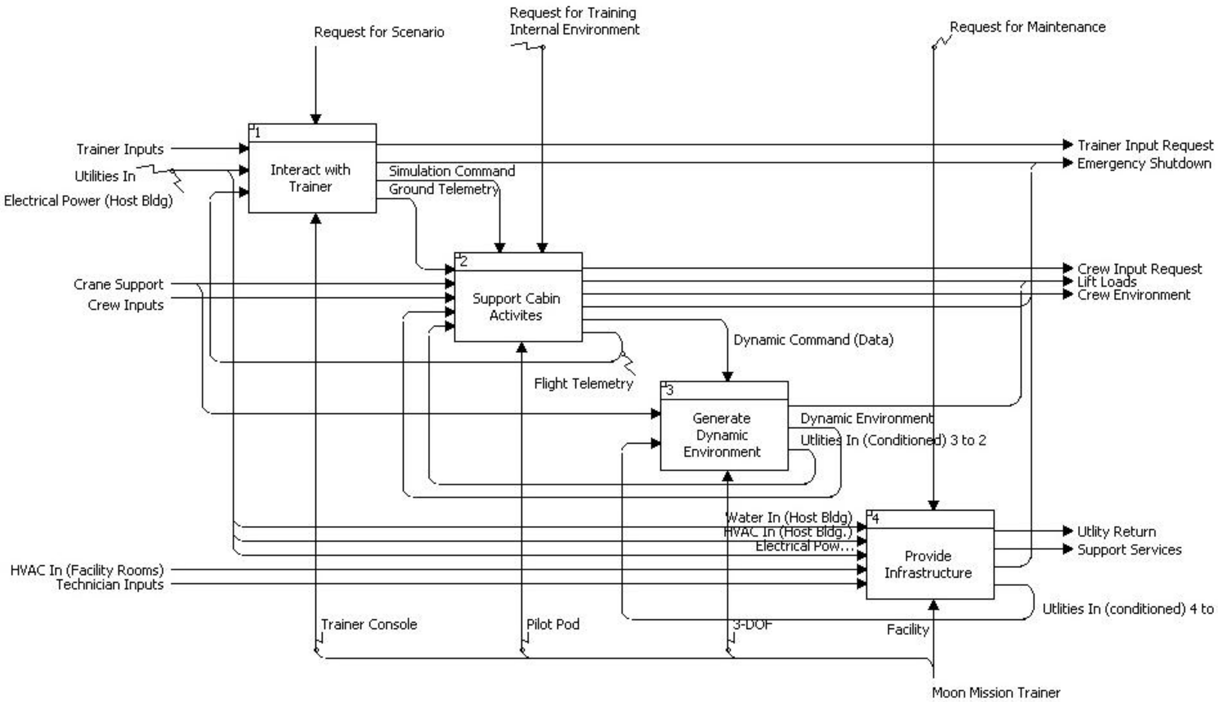

Figure 13. IDEF0 model for the CMT, first level

D. Physical Architecture

The use of a physical architecture tree is common practice in systems engineering and design; in this case, there is a one-for-one definition of a physical element, based on the previous functional architectural tree from Figure 12. Figure 13 shows the physical architectural tree decomposed once again to the second level. It is common to use the physical architecture in order to establish the work breakdown structure (WBS) of a project. The WBS must sum up to the whole of the system, allowing for accurate costing and logical partitioning of work packages.

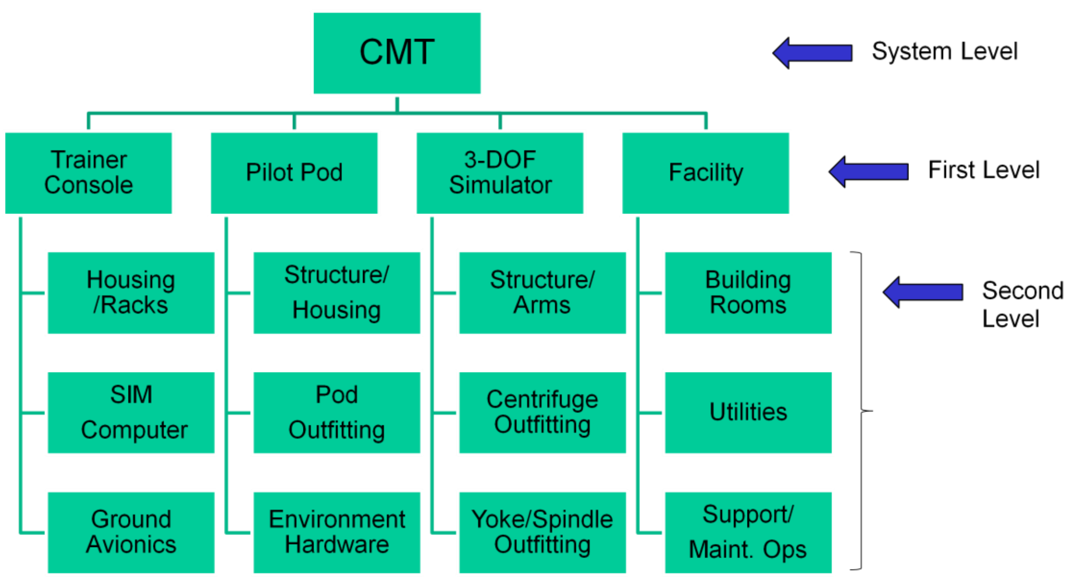

Figure 14. Physical architecture tree for the CMT

E. Interface Definition

An interface is commonly defined as a connection resource for hooking to another system's interface (external) or for hooking one system's component to another (internal). The CMT as a system has both internal and external interfaces. Figure 15 shows a simplified interface schematic of the CMT and several top-level examples of both types. Internal interfaces as shown include the Trainer Console – Pilot Pod (for communication link), and there are many more. The external interfaces to Facilities include Pilot Pod – Crane (for lifting the component), 3DOF Simulator – Floor (for attachment of the centrifuge base) and Routing – Utilities (for transfer of HVAC, electrical and water). Interfaces have inputs, produce outputs, and perform functions which need to be carefully assessed, as they are often the source of failures in many systems. Operational concepts aid in exploration at interfaces, and defining or using existing interface standards is beneficial. Finally, alternative interface architectures should be examined, including assessing the needed functions and choosing the most cost-effective alternatives.

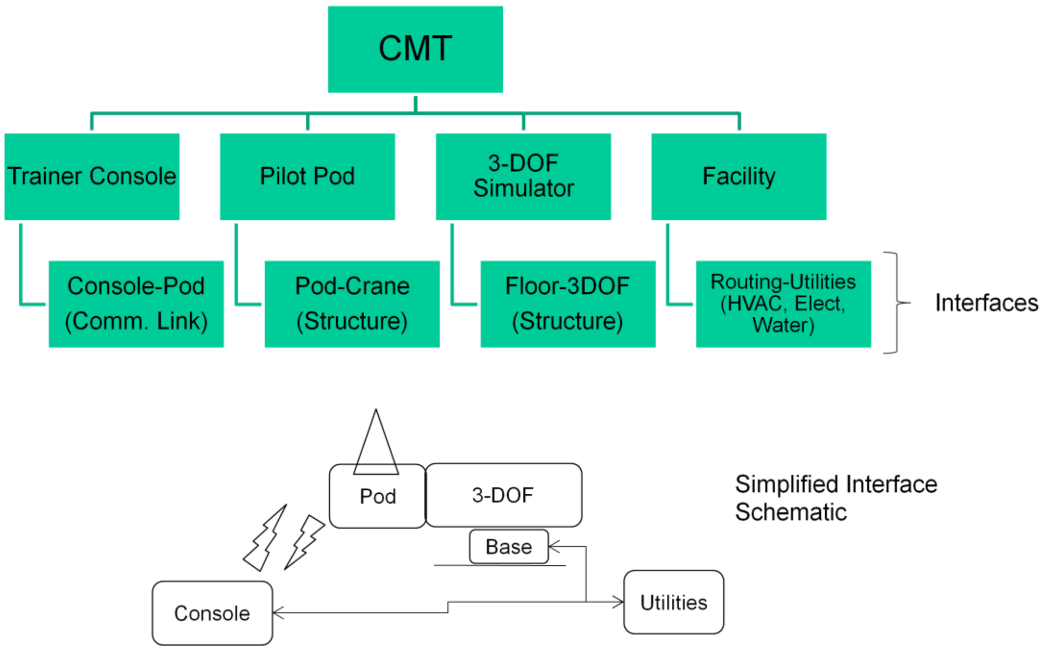

Figure 15. Examples of interfaces for the CMT

F. Physical Description of CMT

At some point in the development process, a physical representation of the system in the form of a descriptive model (such as a CAD model) is generated. Figure 16 depicts one version of the CMT contained within a two story facility. Creation of such models is very helpful in conveying the description of the system to management and key decision makers for the project. An isometric view provides perspective, and cutaways and exploded views are often beneficial when describing a system CAD model. In Figure 16, identification of the physical elements and their relative locations is provided by use of an isometric view of the CMT upper and lower levels. The lower floor view has the upper floor omitted for clarity.

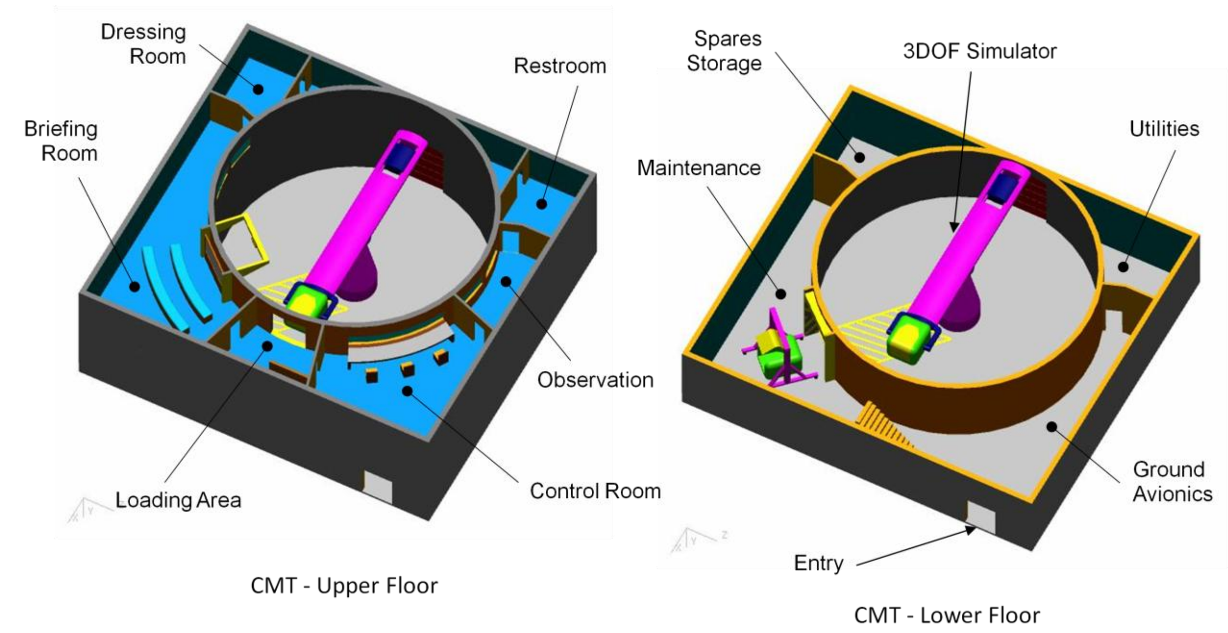

Figure 16. General physical arrangement for the CMT

The facility architecture layout is provided in Figure 17. As mentioned, the CMT would ideally be located in the JSC Building 9 Training Facility, at the south end. After 2010, this building will have the floor space necessary to handle a 65’ x 70’ footprint after the Shuttle mockups are removed. It will be necessary to strengthen the local floor area where the centrifuge is to be mounted, as the total 3-DOF simulator weight resting on the base is over 13 tons. Substantial amounts of power will also need to be routed to the utility room shown in Figure 17. The facility for the full-task trainer includes:

- Overall facility dimensions of 65’ x 70’ x 25’ tall
- 50 foot diameter Simulator Room which houses the CMT
- Control Room, with computers and an observation area for several visitors
- Elevated briefing room for the crew and trainers (outfitted with chairs and lecture screen).
    - Exit doors from this room lead to the platform for loading into the Pod.
    - Some room for suit outfitting will also be available
- Utilities room for transfer of electrical, HVAC and water
- Maintenance and repair shop, and Spares room
- Emergency exits at several locations
- Overhead access with removable top for ceiling crane operations

In addition, the layout for a group of part-task trainers is provided in the lower right-hand corner. Stationary Pilot Pods serve as the trainers. These trainers were added to the architecture when stakeholder feedback was obtained. The portion of the facility for the part-task trainers includes:

- Separate, stand-alone room for part-task training
- Four part-task trainers elevated on stands
- Access walkway to all trainers

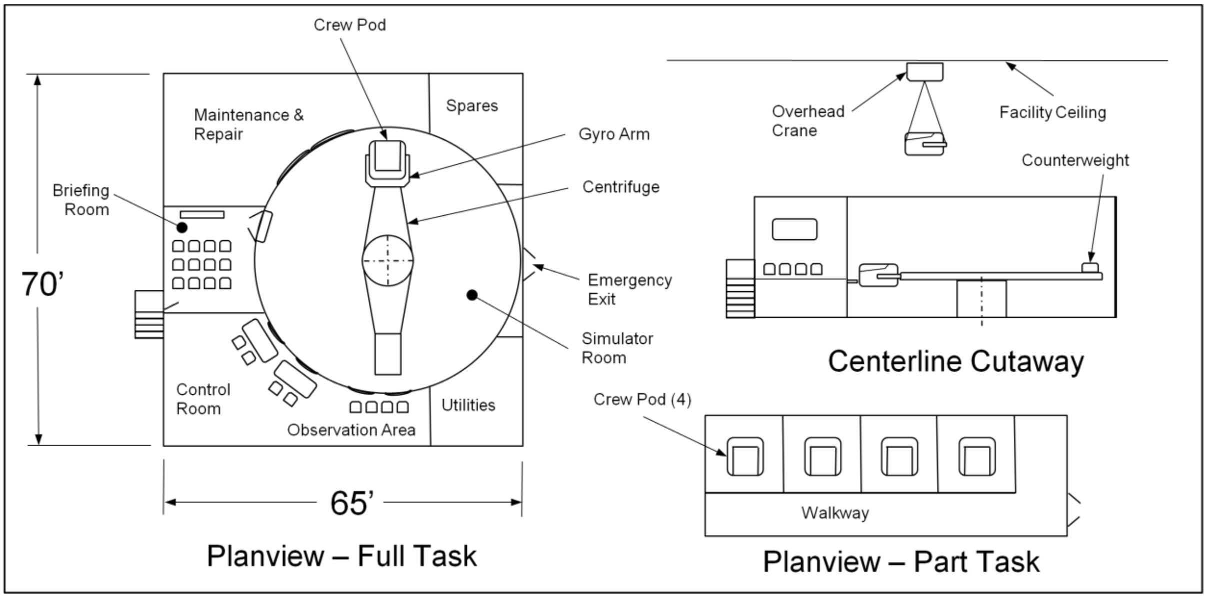

Figure 17. Schematic layout for the CMT full-task and part-task trainers

Further details are provided for the Pilot Pod, one of the highlights of this system. The Pilot Pod houses the training crew and its interior is designed to be as flight like as possible. Cutaway views are shown in Figure 18. The structural housing does not have to look at all like the CEV exterior, and its design is driven by function, rather than form. Some basic details are as follows:

- Fits crew of 4 based on CEV configuration
- Suited or unsuited (Umbilicals for suited)
- Full fidelity interior (Control panel, joystick, seats, forward and horizon windows, etc.)
- Electrical, water and HVAC supply for hot and cold conditions
- Pivot interface for the mounting yoke – also transfers utilities
- Avionics and simulator computers behind seat/pallet

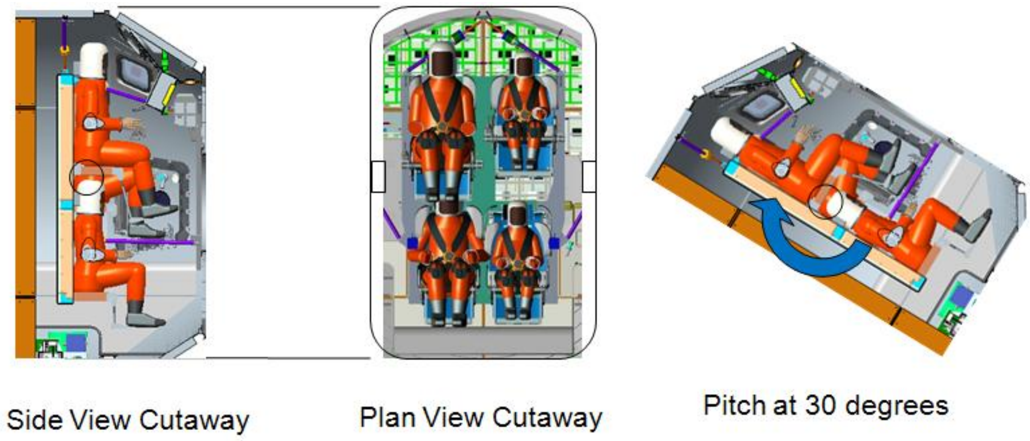

Figure 18. Pilot Pod overview

Additional information is given in Figure 19, showing 2 positions in the side view cutaway, and the general pod shape as referenced to the spindle. Pod functions include:

- Crew loads in horizontal position via swinging door hatch
- The Crew is restrained inside the Pod by CEV type harnesses
- Pod has 2 degrees of freedom, full and continuous 360 degrees (pitch and roll)
- Multi-axis parameters
    - Yaw effects are handled through visual cues (video), rather than mechanical means
    - The Pod pitches 90 degrees to provide a positive G-force experience
    - By rolling 180 degrees and pitching 90 degrees, the crew faces outward to experience negative Gs

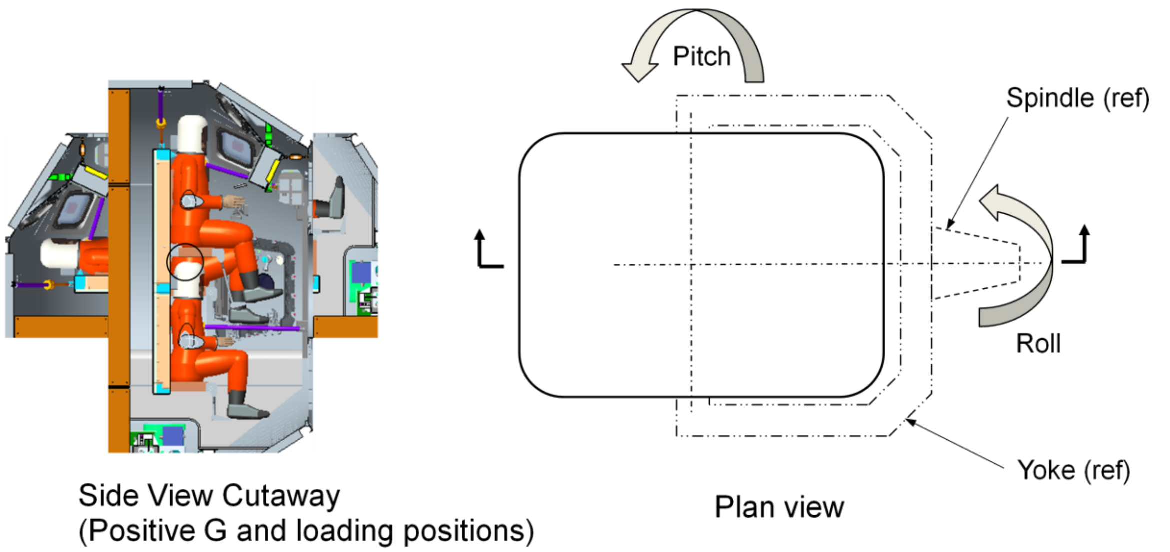

Figure 19. Detailed definition for the Pilot Pod and attachment

VI. Future Spinoffs

One of the key benefits of the CMT architecture includes the ability to be robust in terms of adaptability and reconfigurability. Because the Pilot Pod can be quickly removed and replaced, this allows for completely different pods to be used which represent other space vehicle cabins. In essence, there are unlimited configuration options for cabins, and many potential flight environments that can be programmed. Figure 20 shows the reconfiguration opportunities listed below:

- Multiple uses with CEV and Altair Lander pods – evolves with program maturity (expandable and reconfigurable)
- Reprogramming the simulator provides custom tailored environments as desired
- Grows incrementally through all phases of the Constellation program and provides increasing capability – pay as you go
- CMT can be upgraded to add more arms **-** eliminates training bottleneck

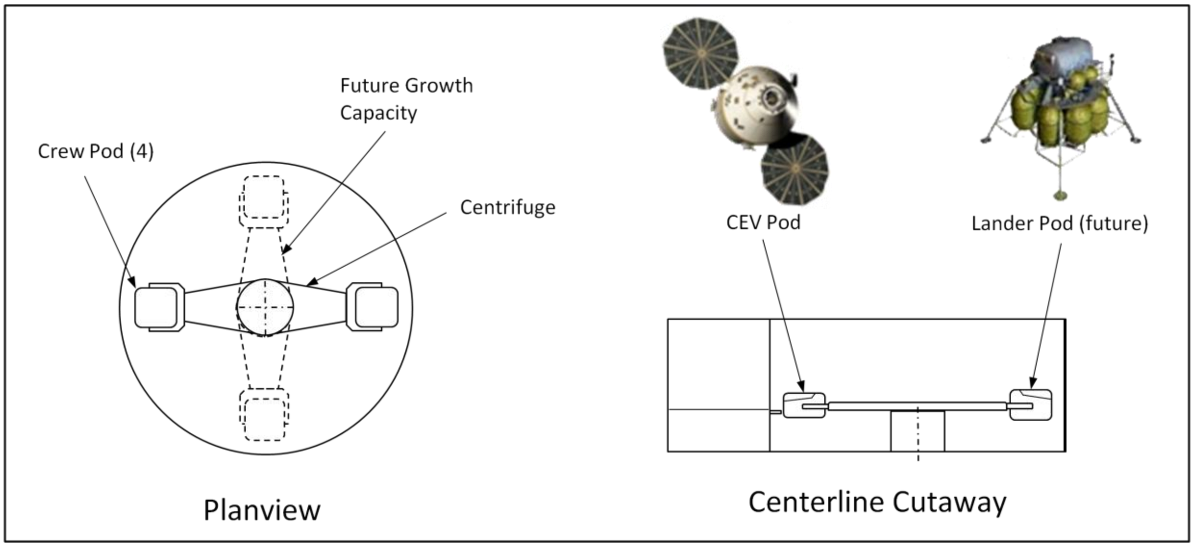

Figure 20. Adaptability and reconfigurability for the CMT

VII. Conclusion

There are currently no simulators in use by NASA that will meet the needs of crew training in a realistic, safe environment. Logistically, by providing an all-encompassing simulator that is as realistic as possible, secondary trainers and systems are eliminated, and significant cost savings can be met, both in terms of development and training. It has been shown that the CMT can utilize an existing facility for additional savings.

In conclusion, the project team has used systems engineering processes to generate a comprehensive, low risk architectural plan to develop and deliver a Crew Mission Trainer that leverages exiting COTS technology, has a target price cap of $40 million, and anticipates delivery on or before January 1, 2015. A multi-arm centrifuge simulator satisfies the customer's needs, because it provides a realistic space environment on the ground for training and in-flight backup testing. The design leverages similar designs are now available in the entertainment industry, reducing risk. The novel system generates sustained positive and negative G-forces, provides sustained pitch and roll rates, and has a fully capable, flight-like cockpit. Unique, computer generated mission scenarios are virtually endless and are anticipated to reach an uncanny level of realism. Such a system would benefit both the astronaut crew and the astronaut trainers. By creating such a realistic environment, the astronaut will be conditioned and ready for nearly any scenario during an actual mission flight.

In addition to producing a novel idea for a dynamic motion simulator, the process facilitated an understanding of the problem and quickly distinguished an efficient solution from several options to one that almost fell onto the paper. The team kept the stakeholders in mind by presenting the design concept and its architecture, and integrated the feedback loop at every step of the way. From an operations standpoint, when we found that a part-task trainer played an important role, we spun-off a static Pilot Pod trainer concept to complement the full task trainer. When the team studied system functionality first (what does the system do), the physical aspect of the simulator was easier to align to the eventual validation of such a project. The ultimate success of a project not only rests with verification (did we build it to spec), but with validation, which asks 'Did the customer get what they wanted?' The systems engineering process as described in this paper was shown to be a successful application of methods which can be applied to projects of similar nature.

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