Functional Integration of Humans and Spacecraft through Physics, Physiology, Safety and Operability

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Abstract— **Design criteria for human-rated space systems can be broken down into four top-level functional categories grouped by parameters of physics, physiology, safety and operability. Starting with a minimal function design baseline, a set of non-negotiable requirements can be derived that provide the requisite physical protection from the space environment and meet the basic physiological needs of the crew, but nothing more. This can be thought of as a 'technically feasible, but programmatically unacceptable' initial solution from which to start the iterative trade study process that will ultimately make the system safer and/or nicer (i.e., more operable). Safety aspects include risk mitigation approaches such as added redundancy, increased factor of safety or consumable margins. Operability can be further categorized into accommodation (what the vehicle provides the crew beyond the bare necessities) and utilization (what the crew does for the vehicle/mission), which can be evaluated through human factors analysis and testing. This framework provides clear and relatively simple guidelines for defining a set of baseline, minimum functionality conceptual design requirements that can theoretically accomplish the stated mission objectives. It can also serve as a verification and validation method to be used throughout the design process for ensuring that any additional features requested to be incorporated into the spacecraft beyond the minimal baseline are systematically rationalized for inclusion. Employing this philosophy from the beginning of a program can help to reduce the typical mass overruns that tend to occur from baselining legacy solutions and to minimize 'scope creep' by making it necessary to rigorously justify each function that is added over and above the minimum baseline in terms of improved safety or operability. This work outlines how a human spacecraft design scheme such as this can be defined and implemented.**

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1. INTRODUCTION

A functionality-driven design process essentially starts with identifying 'what' must be done and then systematically determines 'how' to best accomplish it. For human spaceflight, the 'what' is typically defined as the Mission Statement, which can range from conducting suborbital tourist flights to Low Earth Orbit (LEO) 'hotels' and research platforms to human exploration of the moon, Mars and beyond. Ground Rules and Assumptions (GR&A) can be added as desired to constrain the trade space. With the high-level goal defined, additional insight is attained by developing a Design Reference Mission (DRM) and/or a Concept of Operations (ConOps). These serve to couple the design with its intended use by describing supporting elements and operations across all mission phases and can provide unique insight for identifying requirements that are not always obvious from a vehicle-centric engineering perspective (*e.g., did you remember to bring toothpaste and toilet paper?*)

Various Systems Engineering techniques exist for translating the goals, constraints and operations into functional objectives and quantitative system requirements, defining logical subsystem groupings, selecting and trading off candidate solutions, evaluating and mitigating risks, and ultimately producing a vehicle that will enable the Mission Statement to be accomplished with an acceptable degree of confidence [1]. The functional design process described here serves to begin transitioning the 'what' into 'how' in the form of a conceptual design, which lays the foundation for the subsequent detailed design, manufacturing, verification and operational phases.

2. FUNCTIONAL INTEGRATION OF HUMANS AND SPACECRAFT

Fundamental Design Drivers

From an overly simplified perspective, the overarching spacecraft design goals for human missions can be summed up as keeping the crew *alive*, *healthy*, *happy* and *productive*. These four criteria (bulleted below) define the basic vehicle subsystem functions related to the people on board, and are captured more formally as human-rating requirements.

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- **Alive** – Habitat and Environmental Control and Life Support System (ECLSS)
- **Healthy** – Biomedical Countermeasures, Medical Care and Human Factors
- **Happy** – Crew Accommodations and Psychological Support
- **Productive** – Operational Efficiency in meeting Mission Goals

Human-Rating

In the early days of the space age, the available expendable launch vehicles (i.e., missiles) were generally deemed too unreliable for safe human use, successfully reaching orbit less than 80% of the time. To improve the likelihood of crew survival and mission success, redundancy was added to critical systems, reliability of components was increased, and launch escape systems were developed. The outcome was termed ‘man-rated’, first noted for the X-15 program in the literature reviewed [2,3]. This term became synonymous with the later use of ‘human-rating’. Human-rating in the Mercury, Gemini, and Apollo Programs was centered primarily on increasing safety. As Mercury and Gemini evolved into Apollo and Skylab, however, human-rating began to focus on improvements to operability as well [4]. Skylab and Shuttle Programs subsequently added an emphasis on human performance and health management. [5.6]. The fundamental tenets of human-rating are to *accommodate* the needs of the crew, effectively *utilize* their capabilities to accomplish the mission objectives, and *protect* the crewmembers, as well as ground teams and the uninvolved public, from hazardous events [7,8,9]. These concepts are outlined and summarized in Figure 1.

Figure 1. Fundamental tenets of spacecraft human-rating.

Functional Categories

We have established a methodology that encapsulates the intent of human-rating and addresses risk mitigation and mission objectives, repackaged into four functional categories termed *physics*, *physiology*, *safety* and *operability* depicted in Figure 2 [10].

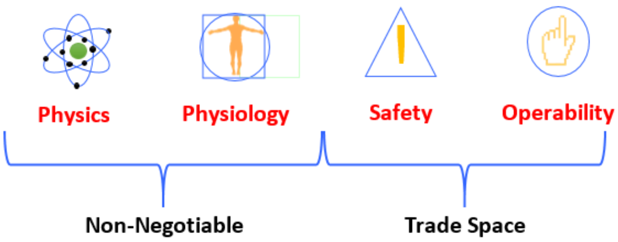

Figure 2. Functional Human Spacecraft Design Requirement Categories

- **Physics** – defines a minimum set of requirements necessary to meet mission objectives primarily in terms of structural integrity and propulsion needs
- **Physiology** – ensures crew is provided with an adequate Environmental Control and Life Support System (ECLSS)
- **Safety** – characterizes risk using Hazard Analysis, Failure Mode Effects Analysis (FMEA), Fault Tree Analysis, Mean Time Between Failure (MTBF) and Probabilistic Risk Assessment (PRA) to estimate probability of Loss of Mission p(LOM), Loss of Vehicle p(LOV) and Loss of Crew p(LOC) as Figures of Merit
- **Operability** – relates design to human performance - ‘*How can ‘ease of use’ be quantitatively differentiated between two otherwise equally capable and safe vehicles?*’

Satisfying this set of ‘non-negotiable’ physical (e.g., pressure containment, rocket delta-V, etc.) and physiological (e.g., O2 provision, CO2 removal, etc.) requirements can be used initially to define a minimum functional baseline spacecraft that can accomplish the desired mission goals albeit with no margin, no redundancy, and no factor of safety. This effectively establishes an absolute ‘minimum mass/functionality’ design. Anything added beyond this baseline must be justified by trade study in terms of cost/mass incurred to make it ‘safer’ or ‘nicer’.

In this manner, the mass fractions of a spacecraft can be broken down by first establishing the minimum baseline physics and physiological components and then tracking add-ons for safety and operability independently, which represents a proxy for the ‘cost’ of each addition. Equivalent System Mass (ESM) is a technique developed to compare design options by relating component level alternatives to propagated impact to overall mass [11].

$$\mathrm{ESM} = \mathrm{M} + (\mathrm{V} \cdot \mathrm{V_{eq}}) + (\mathrm{P} \cdot \mathrm{P_{eq}}) + (\mathrm{C} \cdot \mathrm{C_{eq}}) + (\mathrm{CT} \cdot \mathrm{D} \cdot \mathrm{CT_{eq}}) \qquad (1)$$

ESM = Equivalent System Mass
M = mass (kg)
V = *volume* (m^3)
P = power (kW)
C = cooling (kW)
CT = crew time (crewmember-hour / day)
D = duration (days)
eq = equivalency factor to convert V, P, C and CT to kg

In other words, when comparing two options that have the same base mass but different power requirements, ESM analysis can proportionally penalize the higher power component by including the additional mass that will be needed for the spacecraft power system. Similarly, this can be applied to volume and thermal control, as well as crew time needed to operate or maintain the component. The weighting factors are determined by the specific vehicle design and mission scenario. For example, adding 'crew time' might be a negative impact for ISS, where they are especially busy, but viewed as a positive factor for a transit to Mars where boredom becomes a potential concern. Adding up the mass 'costs' is relatively straight forward but only part of the picture. It is cautioned by the authors [11] that "ESM should rarely be the only metric applied in a trade study. As a cost metric, ESM may not be capable of capturing reliability, safety and performance differences between trade study options".

This leads to a different challenge - quantifying the 'benefits' associated with making the vehicle safer and nicer. From a *safety* perspective, the benefit of overall risk reduction typically boils down to a single figure of merit – probability of Loss of Crew p(LOC). Characterizing *operability*, however, is not yet a similarly standardized process. Our efforts have begun addressing this remaining challenge by establishing a method for quantifying the benefits in terms of operability. Examples of Metrics and Figures of Merit associated with each functional category are indicated as follows.

- **Physics and Physiology**
  - Total mass determined from bottom up analysis of parts
  - Equivalent System Mass equates 'non-mass' parameters to mass equivalencies to compare options
  - Can estimate p(LOM) as a success figure of merit for mission assurance
- **Safety**
  - Probabilistic Risk Assessment provides p(LOC) and p(LOV) as a safety metric
  - Risk to uninvolved public is characterized as Expected Casualties (Ec)
  - How safe is safe enough?
- **Operability**
  - Modified Cooper-Harper Rating
  - Performance Shaping Factors related by a Contributing Factor Map (CFM)
  - Vehicle-crew influences

For spaceflight in particular, this analysis is especially critical since all mass and energy crossing the vehicle boundary must be accounted for in a very unforgiving environment where total mass is typically a primary driver. Ultimately, the extent to which operability can influence safety must also be considered. The conceptual design process is summarized next.

3. BASELINE DESIGN PROCESS

For human space missions, three initial decisions must be made in order to begin sizing the vehicle - mission duration, number of crew, and target destination. From these three parameters, the basis for an initial baseline spacecraft design can be derived [12]. The conceptual design process then proceeds sequentially as follows.

Habitable Volume - The first step is to identify what will be maintained as the habitable volume, which is primarily a function of number of crew and duration. This can be estimated from the Celentano curve [13,14], although more recent analysis by Cohen [15] suggests that there are caveats to this approach. Destination is a factor, mainly due to the effect on usable space in an orbital habitat than is available on a planetary surface with a gravitational field. Regardless of how it is determined, this initial design decision ultimately sets the stage for sizing the vehicle.

Habitat Atmosphere Composition and Pressure - Another related decision point is to select the cabin atmosphere gas constituents and total pressure. For a baseline design, standard sea level conditions are reasonable with subsequent alternate mixes addressed by trade study later in the flow.

Environmental Control and Life Support - From this starting point, the next step is to determine metabolic mass consumable needs, again a function of number of crew and total duration. Estimates for daily oxygen, water and food requirements per crewmember per day provide an initial mass estimate, with the assumption that everything will be brought up with the minimal functionality vehicle and no in situ or recycled resources are yet incorporated [16]. These options are considered later by trade study. Once the consumable masses are totaled, heuristic estimates can be added for containment, tankage, plumbing, etc. as needed to store and distribute each. The remaining Environmental Control and Life Support System (ECLSS) functions can similarly be defined using simple, well known initial solutions such as Lithium Hydroxide for CO2 removal and a condensing heat exchanger for temperature control and humidity removal. A waste collection system for urine and feces completes the primary human input/output needs. In this manner, the remaining basic functions needed to sustain life can be benchmarked with existing technologies to develop a system that will work, but is not necessarily optimized.

Extravehicular Activity – A specialized subset of ECLSS extends to Extravehicular Activity (EVA) if external sorties are part of the mission objectives. When a crewmember is conducting an EVA, the same daily metabolic consumption estimates apply, now being delivered by the suit rather than in the cabin. The infrastructure mass can be estimated from current suit technologies and a decision can be made for whether to baseline an airlock, suit lock or suit port, or simply depressurize the entire vehicle for egressing. As noted above, the solution does not need to be optimal at this point, it just needs to enable the function.

Payload / Crews Accommodations – Specific mission objective-dependent goals drive the need to house payloads. Crew Accommodations (CA), however, must be provided to some degree for any mission profile. This subsystem includes items that are not needed to sustain life, but directly serve the needs of humans such as restraints and mobility aids, food preparation, clothing, hygiene needs, sleep facilities, medical care, and even recreational activities, that are not readily captured in the other vehicle subsystems [17].

Avionics, Power and Thermal – The remaining subsystems are essentially the same functions as needed on satellites. Functional needs of communication and data handling are defined per the mission objectives. These avionics make up most of the additional power consumers. Once they are defined and characterized, the power budget can be summed up. This then leads to defining the energy production and/or storage needs, which can be translated into mass and volume. Any number of baseline systems can be used as a starting point with some insight – ranging from batteries to fuel cells to photovoltaics to nuclear systems. From this total, the heat rejection system can be sized. Assuming minimal heat leak or gain through the structure, the thermal control system is based on human metabolic and avionic heat, essentially on a 1:1 ratio (Watts in = Watts out). The means for dissipating heat from the vehicle can be accomplished by sublimation, evaporation or radiation, again depending on insight and various operational parameters, and can be sized accordingly based on rejection rates determined by the heat loads.

Structures – This above information is now sufficient to make a reasonable estimate of volume needed to house the internal components, which added to the habitable volume, gives the total vehicle pressurized volume. From this information, the pressure vessel and internal structures and mechanisms can be sized and defined. The key aspects in estimating the mass of the outer structure are driven by atmosphere pressure, thermal insulation and to some extent, radiation and Micrometeoroid and Orbital Debris (MMOD) protection, although these can be considered later in the process as risk reduction steps.

This completes the minimum, non-negotiable functionality of a human spacecraft design and sufficiently defines the subsystem requirements needed to develop an integrated schematic connecting all the relevant components and giving shape to the vehicle. The end result provides a systematically-derived, first order mass and volume estimate of the structural elements along with all consumables and subsystems.

Propulsion – The final step is to size the onboard propulsion system and fuel mass required to make the specified orbital maneuvers that are needed to support the mission objectives as determined by launch, orbital and reentry delta-V calculations. Fuel tankage can be estimated from the mass needed for the summed burns and the integrated vehicle layout, mass and volume is now complete. The spacecraft is essentially now a ‘payload’ ready to be launched.

Launch Vehicle – Finally, tallying all of the consumable and infrastructure mass from the above sequence of steps and estimating the overall volume and geometric layout with simple scaled sketches, selection of a launch vehicle can be made to deliver the integrated system to the desired destination. This last step closes the initial iterative loop and also serves as a sanity check on feasibility of launching the baseline conceptual design.

From this rather austere foundation, the requirements based on *physics* and *physiology* as needed to accomplish the mission are satisfied and a point of departure is established for subsequently working to improve safety and operability. In other words, the baseline vehicle will just get the job done if nothing fails, resulting in a ‘technically feasible’ but ‘programmatically unacceptable’ design. Everything added beyond this serves to make the spacecraft *safer* or *nicer*.

4. DESIGN ITERATION

The challenge in this next stage lies in how to quantitatively assess the cost/benefit ratio for each addition desired to reduce risk and/or improve operability. In this context, ‘mass’ can serve as a proxy for ‘cost’ [17]. Integrated mass and safety analysis techniques exist, as described above, with generally accepted standardized methods. No comparable established single method exists for similarly evaluating operability, although various standards and guidelines have been developed for accommodation and utilization [7,18,19].

‘Safer’

Starting with this minimal functionality baseline design, engineers now begin asking a lot ‘what if?’ questions aimed at identifying and mitigating risks, summarized as follows. This process consists of first conducting a Hazard Analysis to identify sources of potential harm. These can be external (e.g., MMOD) or internal (e.g., high pressure tanks) factors. Systems engineering techniques such as a Failure Modes and Effects / Criticality Analysis (FME/CA), Fault Tree Analysis, Mean Time Between Failure (MTBF) and Probabilistic Risk Assessment (PRA) are used to couple ‘what breaks with what happens’ in terms of likelihood and severity, followed by what can be done to reduce the potential outcome.

The end result of the risk analysis process is defined by three figures of merit – probability of Loss of Mission p(LOM), Loss of Vehicle p(LOV) and Loss of Crew p(LOC). LOM addresses mission success and LOC addresses safety. LOV can fit in either category – the mission might be accomplished even if the vehicle is lost and loss of vehicle does not necessarily mean loss of crew occurs. For example, they might have accomplished the mission objectives but safely bailed out during reentry. NASA has established 1/200 as the overall target p(LOC) for commercial spacecraft traveling to the International Space Station (ISS) [9]. This represents a roughly twofold reduction in risk compared to the Space Shuttle, which exhibited an overall mean p(LOC) value of 1/90 toward the end of its 30-year operational lifetime [20].

Of course, the goal is not simply to determine the risk, but to set a baseline for mitigating risk using approaches such as improving reliability, adding redundancy, increasing factor of safety or allocating extra consumable margins. This generally implies added mass or development time, which is a 'cost' of improving safety. In the end, within the certainty of the probability analysis and assumptions, risk mitigation is implemented by the systems engineering process. An open question remains, however, of 'How safe is safe enough?' Ultimately, this is a personal, programmatic or business decision and also has bearing on informed consent content for commercial spaceflight participants [21,22].

'Nicer'

The remaining step in this approach is to assess how effectively the vehicle accommodates and utilizes the crew. In order to improve operability (usability, capabilities, ergonomics, human factors) to the maximum extent practical (or desired), some means of measuring the outcome must be defined and justified by trade study. The basic accommodations (physics and physiology) can be met by design verification as needed to keep the crew alive. Beyond this absolute minimum provision, how is 'nicer' quantified? Similarly how is 'efficient utilization' measured? No single figure of merit exists to our knowledge for quantitatively coupling human performance to vehicle design options. This extends 'verification' (did you build the thing right?) towards 'validation' (did you build the right thing) and represents the relative overall quality of the final design. We have taken steps toward quantifying the influence of the vehicle on crew performance and well-being in our research endeavors.

Our initial effort at characterizing operability was introduced by the field of Human Reliability Analysis (HRA). This led to development of a Contributing Factor Map (CFM) that relates the many different influences of the technical and social domains associated with a human space mission ranging from the organizational culture to the training paradigm and extending to the space environment and vehicle design to human physiology and cognitive function. In other words, the CFM essentially couples all relevant factors to overall mission success. This is used to document specific known influences, referred to as Performance Shaping Factors, and subsequently identify knowledge gaps that might then drive future research needs. The CFM framework also addresses risk analysis and management, exemplifying the overlap between safety and operability [23,24,25].

Beyond this overarching initial framework, we are currently examining in more detail the influence of accommodations (design) on utilization (operations) and vice versa through three measurable human resource categories - *Physiological*, *Cognitive* and *Psychological*. These three resource categories can be characterized using existing metrics and methods such as Profile of Mood States (POMS) and Man Machine Integrated Design and Analysis System (MIDAS), as well as basic anthropometric parameters. Crew performance can also be assessed using techniques such as the Cooper-Harper Rating Scale, Workload, Situational Awareness and prototype evaluation. By integrating the three resource categories, we can get a more complete picture of the crewmember's overall well-being, which in turn, can be used as a proxy for quality of the vehicle design from an operational perspective [26]. A list of specific vehicle design parameters is derived from a subset of the Performance Shaping Factors described by Mindock [27], including the vehicle environment, architecture, habitability, and user interfaces. Our current aim is to develop a comprehensive method allowing comparison between various designs that is evolved from ESM, where we essentially swap 'human performance' for 'crew time' to more fully assess and quantify design choice impacts in terms of system and crew attributes. A key challenge in developing this output metric is to ensure it is sufficiently robust without being overly complex.

Putting it all together

Going back to the '*physics, physiology, safety and operability*' model, we have systematically established a framework built on four doctoral dissertations [17,27,28,29] for tracking mass addition above the minimal functionality baseline in terms risk reduction and operability improvement, collectively illustrated in Figure 3.

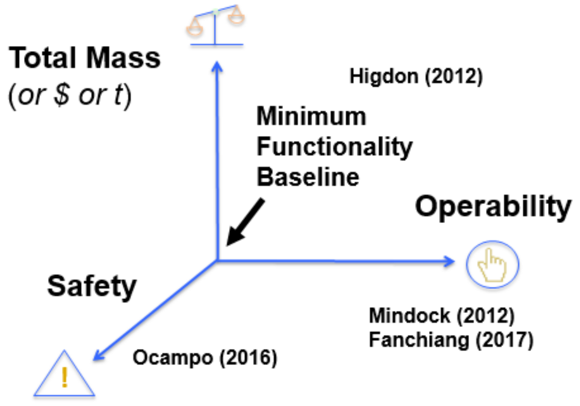

Figure 3. Framework for Relative Comparison of Safety and Operability Indices ($=cost, t=development time)

As noted above, p(LOC) is a generally accepted metric used to characterize overall safety. Our research efforts in this context have been focused more on the question of 'How safe is safe enough?' through analysis of terms and definitions and comparison to common terrestrial transportation modes and adventure sport activities. While this answer is not something that can be 'calculated,' the question can be clarified to avoid ambiguity. Furthermore, the risks associated with spaceflight can be put into perspective for potential participants and spacecraft developers by providing information that can be used to determine a reasonably achievable probability of safe return as a starting point. Defining a similar figure of merit for operability is an ongoing task.

5. SUMMARY

Building on more than 50 years of NASA spaceflight experience, the nascent commercial space transportation industry is now opening exciting new opportunities that will make spacecraft design a more mainstream activity. Our efforts are aimed at helping this new endeavor, as well as space exploration, be successful in a manner that is as safe and efficient as practical. This proposed framework provides clear and relatively simple guidelines for defining a set of baseline minimum functionality conceptual design requirements that will theoretically meet the stated mission objectives. It can serve as a verification and validation assessment query to be used throughout the design process to ensure that any additional features requested to be incorporated into the spacecraft beyond the minimal baseline are systematically and quantitatively rationalized before inclusion. Employing this philosophy from the beginning of a program can help to reduce the typical mass overruns that tend to occur from baselining legacy solutions and to minimize ‘scope creep’ by making it necessary to rigorously justify each function that is added over and above the minimum functional baseline in terms of improved *safety* or *operability* metrics.

In general, the categories of *Physics, Physiology* and *Safety* are addressed by standard Systems Engineering techniques that yield quantitative and requirements-based outcomes to ensure that the design will ‘probably’ (pLOM or pLOV) accomplish the mission and ‘probably’ (pLOC) be safe. The *Operability* parameter is based on Human Centered Design and is typically more qualitative and creative, which if done right, will help ensure that the design will be nice(r)!

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BIOGRAPHY

***David Klaus** obtained his BS in Mechanical Engineering from West Virginia University in 1984 and promptly embarked upon a career in the space program, initially working as a Shuttle Launch Controller at the Kennedy Space Center in Florida and supporting planned flights from Vandenberg AFB in CA, and later moving to Mission Operations at the Johnson Space Center in Houston. His professional experience spans shuttle life support and EVA systems. In 1990, Klaus joined BioServe Space Technologies and began graduate studies at the University of Colorado, where he obtained his MS and PhD in Aerospace Engineering Sciences. He is now a Professor in the CU Aerospace Department and has been involved with BioServe in varying capacities for over 25 years, serving as Associate Director from 1999-2015. Since 2010, he also leads a CU team as PI on the FAA Center of Excellence for Commercial Space Transportation. Prof. Klaus’s academic career has been focused on establishing a graduate curriculum in Bioastronautics addressing essentially all aspects of human space flight.*