ABSTRACT
This paper discusses the authors’ experiences and lessons learned through designing and constructing small- and large-scale robotic prototypes and the fully integrated use of VR and AR for design. Also of focus here are the methodological tools utilized to implement this student-led research in an interdisciplinary educational environment, as well as the design explorations of Mars habitation systems. Through the systems engineering approach, students will generate ideas that may or may not make it to the final design development stage, but may potentially be valuable to future real exploration habitats and mission architectures. The final prototype allows an assessment of the focus parameters, which are the vessels’ transformation capacities and layout adaption. The design objective of this project is to examine strategies for commonality between an interplanetary vehicle (IPV) and a Mars surface habitat. The presented design proposals address this challenge to create a common habitation system in both habitats so that crew members will be familiar with the layout, function, and location throughout the expedition. The design tools operate at the intersection of architectural layout design, mechanics, and structural design, and use origami folding techniques and structural form-finding concepts to generate shell action rigidity. In addition, the project develops a strategy for mobility and transformation of the surface habitat prior to its transformed configuration. The value here lies in understanding lessons from this strategy for both the design process as well as efficiency and optimization in design as a model for terrestrial design.
INTRODUCTION

The project has several primary areas of focus that are tied together within a collaborative design workflow. These include a design process that used a massive variety of virtual and physical tools, including CAD and BIM models, scripting and data analysis, virtual reality (VR) and augmented reality (AR) simulations, robotic prototyping, as well as small- and full-scale physical models.

This project was carried out through a grant from NASA, which benefited directly from the design and prototyping of a layout with common constraints with respect to both non-earth surface and space habitats. In-space habitats are at a very high technology readiness level (TRL), and yet surface habitats are at a very low TRL. The design(s) will benefit NASA in helping to close the gap.

TRLs are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the project’s progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest (Mankins 2009). TRL 1 is essentially the initial idea, which is translated into future research, and the readiness levels step up sequentially to TRL 9, which would be full development. Active research and design is TRL 3, which looks at viability and is also where proof-of-concept models are developed and the design is ready to proceed. This project was essentially provided with a TRL 1 from NASA and developed to a TRL 3, at which point the final technical report was delivered to NASA.

In this project, the idea was that an integrated design approach provided a strong quantitative and objective modeling system that allowed for a comparative evaluation of design solutions and the ability to assess various comparative configuration options inclusively.

The entire project was carried out with a multidisciplinary team that involved faculty and students from three departments across two Colleges (Environmental Design and Engineering). The core of the work was done by architecture students (ARC) and enriched by engineering students (ENG). The project hinged on upfront foundational research and a survey of Interplanetary Vehicles (IPV) and surface habitats. The design began with the understanding of nine points distinguishing an IPV habitat from a surface habitat and sought ways to find commonality among the layouts without compromising the constraints concerning each. This strategy fostered a criteria-based down-selection through comparing alternatives and evaluating their relative merits.
The project followed a sequence closely connected with the architectural design process that was carried out in three stages: research, design and prototyping. The general stages of investigation are divided into four phases: 1) background research and survey; 2) requirements and constraints definition; 3) develop layout design concepts; and 4) single final design concept development.

In addressing the technical requirements, the concepts primarily focused on three-dimensional space-planning, articulated through a series of subsystems constraints investigations.

BACKGROUND RESEARCH AND SURVEY
Consistent Definition of Technical Objectives
This project addressed the challenge to create a habitation system that has commonality in both the in-space and surface habitat designs so the crew will be familiar with the layout, function, and location of everything in the surface habitat when they arrive on Mars. The design was carried out within the constraints as posited in the challenge provided by NASA: “A typical Mars mission sends a crew of 4-6 persons to Mars and back on a ~1000-day mission. This includes about 250 days outbound, 500 days on the surface, and 250 days on the return. The in-space transfer habitat is in ~0g unless it is rotated to generate an artificial gravity, and the surface habitat is on Mars at ~1/3g.”

Research and Survey
The project began with a comprehensive study of space architecture habitat precedence. Within each study the team specifically examined the defined constraints concerning each habitat, including the following: radiation shielding, pressure ports, EVA airlock, laboratory facilities, countermeasures against weightlessness, gravity orientation, life support, safety and reliability, and construction and materials.

REQUIREMENTS AND CONSTRAINTS DEFINITION
Within the requirements and constraints definition (Phase 2), students working in teams first cross-examined the nine constraints outlined in Phase. Working within the commonality of these constraints, they then comparatively analyzed a number of specific precedents that were either: combined transfer/surface habitats, separate deep space/transfer habitats, or separate Mars surface habitats. These projects are related and interconnected, but the final objective was to identify issues of habitability via the context of commonality within the constraints of applicable gravity regimes, pressure vessel integrity, radiation protection and layout adaptability. Each of the precedents were analyzed and presented with a Powerpoint that remained on a server with the associated technical paper as a compressed resource for the design process. Although the valuable precedent is not further articulated in this paper, the cross-referenced projects are listed in the table below with the associated papers listed in the citations. The reference table of precedent was based on previous comparative studies of space habitat compatibility (Cohen 1997).
Alternative Prototype Concepts for Mars Mission Habitats

<table>
<thead>
<tr>
<th>Combined Transfer/ Surface Habitat</th>
<th>Separate Deep Space/ Transfer Habitat</th>
<th>Separate Mars Surface Habitat</th>
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<tr>
<td>NASA MDRM 1.0, (Hoffman 2011)</td>
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<td>Griffin 2014</td>
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<td>MarsOne 2012</td>
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Table 1. Alternative Prototype Concepts for Mars Mission Habitats.

DESIGN APPROACH AND TOOLS UTILIZED

The multidisciplinary team involved faculty and students from three departments across two Colleges (Environmental Design and Engineering). The core of the work was done by architecture students (ARC) and enriched by engineering students (ENG). The engineering students were primarily from civil engineering for their expertise in systems engineering, manufacturability, cost analysis, and materials selection.

Methodological Tools Used to Implement this Student-Led Research in an Interdisciplinary Educational Environment

The down selection of student projects created a progressive competition, which allowed for the selection of best work through methodical evaluation of its depth and quality. At this early point the students worked in teams consisting of 4 architecture students with 2–3 engineering students in the context of an upper-division studio open to graduate students.

DEVELOP LAYOUT CONCEPTS

Phased Approach to Downselecting

Initially nine (9) designs were developed by the interdisciplinary teams with 1:10 scale physical models that successfully demonstrated the key aspects of the designs related to construction and materials. Students worked in teams of four to produce complete architectural drawings and physical models of selected independent designs (strategies). The nine initial concepts are shown in Figure 4 as clustered by conceptual relevance.

Analyze, Evaluate, and Synthesize Concepts

The conceptual designs were compared and evaluated based on the relative merits of the designs against a set of criteria that provided the framework for evaluating potential design and engineering options. The designs were then down-selected to three final concepts to be further developed. An internal evaluation system was used to define the criteria for selecting a single final concept. A point-based checklist was created by which an inclusive range of performance aspects were judged (Figure 5). The measurable criteria was used to assess how well each design satisfied all of the technical requirements, as well as other difficult-to-assess architectural issues such as comfort, ergonomics, aesthetics, and constructability.

Out of the nine proposals three strong concepts were chosen and teams were redistributed into larger interdisciplinary teams of 12 students with similar contributing design approaches (Figure 6). The concepts were subsequently developed and again the point-based checklist was...
used to arrive at down-selecting to a single final concept (Figure 7). In addition, the final concept was selected in part because it developed a unique strategy for mobility and transformation of the surface habitat prior to its Class II configuration.

Workflow and Tools
This project hinged on a building information modeling (BIM) approach that was leveraged in two principal ways. First, the BIM modeling was used for an investigation of pressurized module geometries and layouts, in such a way that facilitated linking with other system engineering modeling techniques for the tracking of the CAD models, requirements, dependencies, and subsystem integration. Second, a diagnostic strategy was derived from the BIM virtualization. The project integrated design optimization of additive printing devices as an iterative process of design through the BIM model, which is directly tied to fabrication. The BIM capability is relevant to very long duration missions without resupply, because the computational model of the habitat included every piece of equipment, every stowage volume, every component of floor deck, all utility systems, all interior secondary structures, etc. Although the process began with a traditional BIM software (Revit), for the design explorations we quickly turned to a more dynamic modeling software (Rhino) using a script with Grasshopper and Dynamo software. The BIM approach was therefore used to evaluate different volumetric layouts based on quantitative data. A schematic of the final programming adjacencies in the rolled and unrolled versions of the same habitat are shown in Figure 5.

Transformation of IPV to Mars Surface Habitat
In a series of origami experiments, students researched how the IPV geometry could transform into the Mars surface state. It needed to be ensured that the pressure vessel would not be perforated and there would be no redundant material that could “bubble” out when the vessel is pressurized. Additionally, the goal was to find a configuration that allowed a structurally efficient cross section.

The mechanics of the paper model were tested in a series of CAD models using Rhino and Grasshopper definitions. Three groups of elements needed to be defined: struts with a finite length, joints (and their allowable freedom on rotation), and adjustable struts. As the geometry unrolls the blue struts elongate. In reverse that means that these struts can be utilized to control and define the state of the geometric transformation. By unrolling into the rectilinear box shape, the geometry loses its structurally efficient round shape. In the unrolled state the sides, which are configured like a truss, are now structurally irrelevant and can be altered. The sides can now fold outward in the center. This degree to which the folding occurs is controlled by the identical adjustable strut that was used to unroll the

FINAL PROTOTYPE DESIGN: CR-1
The design of final prototype’s goal was to provide tangible evidence of the proposed concept. The focus was shifted from the 1000-day mission to the detail design of what was now called CR-1 (Cal Roli1). The most important aspects that needed resolution were as follows:

- The CR-1’s transformation mechanism that would allow the IPV to function and maintain its structural integrity on 0g and in the Martian gravitational environment.
- The program layout had to be designed allowing all components to be preinstalled with full functionality before and after the transformation
- Allowing a limited mobility on the Mars surface

With the beginning of detail design the question of available materials and their performance arose. The student research identified the main technical design parameters as the pressure vessel and the gravity regimes. The atmospheric pressure on the Martian surface averages approximately 6.0 mbar. This is about 0.6% of the pressure required for the interior of a Mars habitat (1.000 mbar). The gravitational regime on the Martian surface is about 0.38g. This means that design requirements due to pressure differential would outweigh the gravitational design criteria. The CR-1 design needed to assure a structurally efficient pressure vessel in all states of its mission, in IPV mode and in habitat mode.
geometry. Figure 12 illustrates the change in cross section as the length of the blue struts is reduced.

Translation into Final Design
As the CR-1 unrolls from IPV mode to habitat mode, additional roof surfaces open up. These areas are covered with an expandable multiple layer fabric with an outer protective layer made of thin composite scales to shield against radiation. The layout was designed to be equally functional in IPV mode as in the deployed configuration in a gravitational environment. All components are attached to rigid surfaces.

MOCK-UP AND VR
To best develop the project students split up into four groups to produce three final products:

- A fully detailed virtual reality (VR) experience of the project
- A full-scale pavilion representing two segments
- Small-scale robotics for surface motion and unrolling
- A quarter-scale model with a fully functional transformation mechanism

VR Experience
The project was fully modeled in Rhino3D. The VR experience was generated with the Enscape plug-in for Rhino using 3D headsets. The VR model allowed us to move through the model in IPV and the deployed mode. Various views of the interior VR model can be seen in Figure 14.

FULL-SCALE PAVILION FOR AR
The full-scale mock-up was constructed using hollow section tubes, plywood sheathing, and PTFE fabric. All of the working drawings were computationally generated by extracting the geometry from the VR Rhino model.

The pavilion served multiple purposes. It illustrated the scale of the project and gave a sense of the design’s space and proportions. The pavilion was the basis for the project’s augmented reality (AR) experience. Figure 15 shows the overlay of the augmented environment on the existing pavilion. This allowed us to verify the efficiency of the designs layout and the circulation concept.

Small-Scale Robotics for Motion and Unrolling
Small-scale robotics were used with a “terrain” base and two models that explored alternative designs for both mobility and unrolling. An artificial terrain base model, which measured at 5 feet wide by 8 feet long, was created to simulate the terrain and was used for two models to navigate (Figure 16). Simple Arduino and servo motors were used for the models.

Quarter-Scale Model with a Fully Functional Transformation Mechanism
The transformation mechanism was mainly done through prototype experimentation. Students built partial models at quarter scale to understand the required materials, elements, and their structural requirements until they were confident to build the final fully functional model that would allow them to demonstrate the CR-1’s mobility and the robotic unrolling from the IPV mode to the deployed mode (Figure 17). The prototype was then taken to a desert environment to demonstrate autonomy on a terrain that would simulate the Mars surface (Figure 18).

CONCLUSION
Designing for different gravitational environments adds new elements to the design equation that lead to unforeseen hurdles. The project required us to “rewire” the students’ way of thinking by creating an awareness that an intuitive approach to the design problems is in most
cases not successful. In this project’s case, a very intensive introductory research phase was carried out to fully understand the design parameters. From the implications of a 400-day mission to material sciences and the physics in different environments, everything needed to be considered when making design decisions.

The point of the investigation was to drive out new and innovative ideas for space habitation. This project proposes a unique mobile habitat with commonalities within the constraints of both surface and space habitats. In-space habitats are at a very high technology readiness level (TRL), and yet surface habitats are at a very low TRL. The designs presented here will help in closing the gap. Through the design approach, students generated many ideas that may or may not have made it to the final design development, but may potentially be valuable to future real exploration habitats and mission architectures. Collecting and coordinating 3D models, BIM, and other information from distributed teammates was also essential. As building systems and processes become more complex, teamwork and workflow takes on a critical role in contemporary design projects. Through the collaborative design environment, this project illustrated an online collaborative workflow for the design of a habitat that includes an innovative BIM output method as well as an inclusive design process.

ACKNOWLEDGEMENTS

This project was made possible by the generous grants and support from the following:
• 2018 NASA X-HAB Academic Innovation Challenge
• National Space Grant Foundation
• Trimble (Formerly Gehry Technologies)

Students
Laszlo Andrasi (Architecture), Sin Gwon Baek (Architecture), Sorvito Arengiado (Architecture), Lucas Borghese (Civil Engineering), Johnny Busch (Architecture), Erick Cerano (Architecture), Courtney Chan (Civil Engineering), Zheng Chen (Construction Engineering), Sonny Contreras (Architecture), Javier Correa (Architecture), Samuel Cruz Prado (Architecture), Ryan Dacanco (Architecture), Evanna Diaz (Architecture), John Duguiil (Civil Engineering), Lalo Espinoza (Architecture), Jocelyn Hernandez (Architecture), Ricardo Hernandez (Civil Engineering), Qiting Huang (Architecture), Billy Jimenez (Civil Engineering), Charles Kayser (Civil Engineering), Sanhloc LeHuynh (Architecture), Carmelle Luminarias (Architecture), Miguel Magpantay (Civil Engineering), Giancarlo Manglicmot (Architecture), Sharis Manoukian (Architecture), Skyler Maroste (Architecture), Eduardo Martinez (Architecture), Franco Mellone (Architecture), Gemme t. Ng (Architecture), Anh Nghiem (Civil Engineering), Gem Nguyen (Architecture), Andrea Nuno (Civil Engineering), Victor Orozco (Civil Engineering), Jad Osseiran (Architecture), Larry Phong (Architecture), Katherine Pischchik (Architecture), Nick Ramirez (Architecture), Marc Rudy (Architecture), Daniel Sanchez (Architecture), Madonna Sole (Architecture), Tyler Thein (Architecture)
REFERENCES


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Figure 5: © Michael Fox

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All other drawings and images by the students listed.

All other photographs of student work by Michael Fox.
Michael Fox is a Professor in the Department of Architecture, College of Environmental Design, at Cal Poly Pomona. Focus: Project Coordination/Design/Construction. Mr. Fox served as the PI and coordinated the project and teach the core courses in systems design, architectural design studios and analysis.

Marc Schulitz is an Assistant Professor in the Department of Architecture, College of Environmental Design, at Cal Poly Pomona. Focus: Design/Construction/Structures. Mr. Schulitz will serve as the Co-PI and will teach the core courses in systems design, architectural design studios and analysis. His students will participate in all aspects of the project.

Mikhail Gershfeld is a Professional Practice Professor in the Department of Civil Engineering at Cal Poly Pomona. Focus: Design/Structures. Mr. Gershfeld will will teach the core courses in systems design, architectural design studios and analysis. His students will participate in all aspects of the project.

Marc Cohen has vast experience in the space industry, including as a past Lead Human Systems Integration Engineer, Northrop Grumman Integrated Systems. His primary focus is on design research for the aerospace living and working environment for space habitats, space stations, lunar and planetary bases, as well as, human factors engineering design of space work stations, EVA airlock, and crew accommodations.