Full-scale Architectural Simulation Research for Space Station Freedom and Exploration

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Abstract

In developing the architectural design for habitable space environments, a critical step is the design and construction of full-scale architectural mockups to simulate the designed environment.. Representations, either drawn by hand or by computer-aided design (CAD), and scale models are essential steps, but a major architectural research and development step for a space living and working environment is to design and build a full-scale mockup. Full-scale simulation mockups are appropriate to meet these specialized needs, which are increasingly narrow as virtual reality technologies become more powerful.

This paper review s three moderate fidelity mockup simulations that the Space Human Factors Office completed during the formative Space Station Advanced Development Program and one project that is under development for planetary exploration. The Space Human Factors Office at NASA Ames Research Center built a Space Station Proximity Operations Simulator that included an active computer graphics three-screen display, a prox–ops work station and representative crew cabins. The SHFO developed a Space Station Wardroom mockup in collaboration with the Southern California Institute of Architecture, for which a major focus was the design of a deployable wardroom table. The Space Human Factors Office also collaborated with Man–Systems Integration Branch at NASA Marshall Spaceflight Center on the design of the United States Laboratory Module, providing a detailed design of the Element Control Work Station and a deployable videoconference table.

This paper also previews plans for the Human Exploration Demonstration Project Habitat for a planetary surface outpost or trans Mars vehicle, under development at Ames Research Center. HEDP will take an integrated technology approach that goes far beyond traditional static simulations. This paper presents a taxonomy of types of architectural simulation and the degrees of control vs. realism in research design.

Introduction

When I prepared the abstract for this paper, I expected just to describe the work on the three full-scale mockup projects related to the space station. However, the developments over the past five years in computer–aided design (CAD) and virtual reality technologies, since the work on these projects started, compel me to approach this paper differently. Computer design and representation capabilities allow designers and engineers to replace some of the drawing, scale model building and full-scale mockup steps in the design process. Boeing Airplane Company has even skipped the traditional manufacturing mockup stage in developing the 777, proceeding directly from their CATIA CAD system to actual production. What is the role, if any, of full-scale simulation mock-ups under such a tremendous advance in representational technology?

On the other hand, full-scale simulation offers the unique quality that it is human–size. An observer or a test subject can go into it, see it, touch it, hear its acoustical qualities (however flawed, but different from the surrounding environment) and even smell the glue. These qualities, especially the ability to physically enter the artificial world have a verisimilitude and a persuasive power about the nature of the simulated design that is difficult or impossible to achieve in any other way, although virtual reality technology offers the prospect of some inroads in this area. These choices of computer representation versus full-scale physical simulation raise a set of questions and issues that I discuss for the purpose of understanding why and when to build a full-scale architectural simulation.

Simulating Future Space Environments

Because access to space is so difficult, dangerous and expensive, almost all disciplines in engineering, operations as well as architecture attempt to simulate every aspect of space that they can in developing a space vehicle or module before finalizing the design. These simulation technologies often involve sophisticated computer simulations, high fidelity engineering testbeds and complex operational scenarios. These simulations all involve, to varying degrees, the creation of artificial environments through physical architectural simulation of virtual simulation technologies.

Artificial Environments

Full-scale architectural mockups played a vital role for the Space Station Advanced Development Program and definition studies and will continue to be vital for certain aspects of space exploration architecture. The essence of architectural simulation is the creation of an artificial environment, which may serve a variety of purposes, depending upon the designers' intentions. Creating artificial environments is an essential part of many design, engineering and research endeavors. Herbert Simon went so far as to describe designing itself as "the Science of the Artificial," after which he entitled the book [Simon, 1981].

Physical Architectural Simulation

The essential question for architectural simulation research is for what purposes full-scale simulation environments or mockups will continue to be appropriate. To be meaningful, the creators must place full-scale architectural simulation mockups within a research program or systematic design inquiry. Because of their significant expense, full-scale simulation will become increasingly less attractive as virtual environments become more accessible and less expensive.

Virtual Architectural Simulation

The new generation *computer aided design* (CAD) and *virtual reality* technologies compel a reexamination of the role of full-scale mockups. Virtual environments offer many simulation capabilities that are not possible with full-scale mock-ups, especially the opportunity to experience the artificial reality remotely — obviating the need for a large, highbay facility in which to build a mockup or the necessity for observers to travel to see it. Proponents of virtual reality make many claims for the potency of their new medium of representation. Probably there will be a revolutionary effect upon the way architects design and the products that they design using virtual techniques, comparable to the revolution embodied in the Renaissance as a partial result of the advent of perspective drawing as a design tool.

Physical Reality versus Virtual Reality

However, the use of CAD or virtual reality as a design tool or as a representation of a design, however spectacular, is still qualitatively different than a concrete, tangible and human scale embodiment of that design. This difference has profound implications for human knowledge, experience and the ability to conduct research – particularly research that involves more than one human "subject" at one time. This distinction between representation and embodiment is hardly new; it was described most succinctly by Emmanuel Kant in Critique of Pure Reason [Kant, 1781].

> Perception is empirical consciousness, that is, consciousness in which there is at the same time sensation.[1]
>
> Experience is empirical knowledge, that is, knowledge which determines an object by means of perception[2].

Although Kant did not anticipate the advent of computers or virtual environments, his distinction between perception and experience corresponds to the difference between virtual reality and full-scale architectural simulations. Virtual representation can be satisfactory if it succeeds in creating a convincing combination of sensation and consciousness (which is perhaps why it has earned the nickname “electronic LSD”). Full-scale architectural simulation succeeds if it creates an empirical knowledge of physical objects or systems. Whereas virtual reality remains a domain for individual perception, full-scale simulation includes the potential for a number of people to experience interacting with the artificial environment and within it.

Virtual environment technology will find many applications involving individual perceptions. But, space missions are team efforts involving crews of two or more astronauts who must work together in the unique conditions of space. So long as this condition holds true, there will always be a need to provide full-scale architectural simulation capabilities in which to experiment with operational procedures, develop and evaluate hardware and practice space missions with the whole crew at one time.

Architecture and Architectural Research

These developments in representation compel an examination of the question of what is the difference between representation and design, and between design and research and to examine the common assumptions about architecture and architectural research. Historically, architects have developed numerous definitions of architecture, focusing on form, structure, shaping spatial volumes or functionality and the art of creating these attributes. However, for the purpose of this discussion about simulating habitable space environments, consider this research-oriented definition:.

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[1] Emmanuel Kant, Critique of Pure Reason, p. 139.

[2] Ibid., p. 145.

> ***Architecture is an integrative discipline that seeks simple design solutions to complex human–environmental problems.***

These *Complex Problems* may be aesthetic, climatic, cultural, economic, environmental, formal, functional, political, social, and technical. These simple solutions are primarily perceptual, organizational and physical.

What is Architectural Research?

Given this definition of architecture as an integral discipline that that approaches the frontiers of the "human-environment interface," what is architectural research? There are many traditions of research in architecture that cover a very broad range of approaches: form, geometry, history, space, structure, design method, envelope performance, and human behavior to name a few. In the architectural simulation domain, where the researcher is often the same person or on the same team as the designer, it is vital to propose a definition/scope of architectural design research.

> Architectural research design requires ***creating new knowledge*** about the designed environment that is reliable, reproducible and verifiable. Full-scale Architectural Simulation research involves designing and constructing the artificial, physical environment in which to conduct the inquiry.

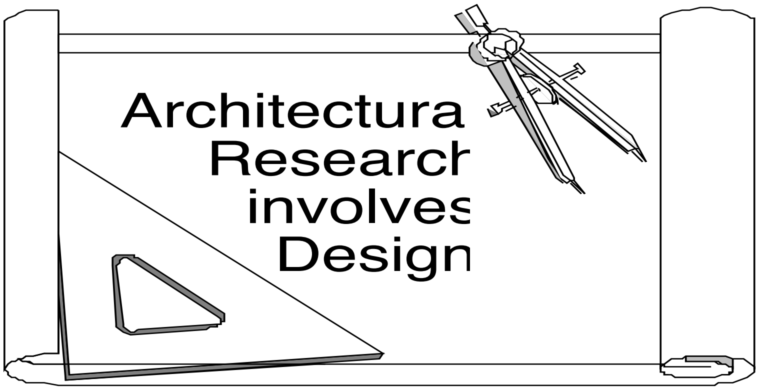
The purposes for full-scale architectural simulation include: Developing new concepts, techniques, methods, technologies and structures, finding optimal design solutions to meet human performance needs, and, protecting the inhabitants health and safety. Safety is a critical requirement both for space habitats and terrestrial architecture. The knowledge and ability to protect the public's health and safety is a fundamental requirement for a professional license in architecture in the United States. Because the space environment is so much more unforgiving than the terrestrial environment, the commitment to safety through architectural design research must begin with the Earth standard as an absolute minimum and go far beyond it.

In summation, the three key characteristics of Architectural Design Research through full-scale simulation are:

> 1) Measuring and evaluating the artificial environment and its interaction with the natural environment.

2) Measuring and evaluating human and human/machine interaction within the designed environment.

3) Measuring and evaluating human-environment interaction with the designed environment.



Caveats

Having stated the salient characteristics of architectural design research through full-scale simulation, it is important to note also several caveats:

1) Architectural research necessarily involves architectural design. This caveat is particularly important when dealing with behavioral research that may tend to discount the physical reality of the environment in favor of perceptual and cognitive explanations, in the interest of psychological theory building. A more than semantic problem may arise between research ***in*** design (where design is the proper subject of the research) and experimental research design (where the purpose of designing is to set up an experiment to obtain statistically valid data).

2) The pitfall for most research-naive designers is to simply dream up something creative and call it research. Merely creating a new design is not the same as creating new knowledge.

3) A new design does not qualify as product of research unless it can prove verifiably that it is better than previous designs and explain why.

The Purpose of Full-scale Architectural Simulation Research

Having discussed the distinction between virtual and physical environments and the salient characteristics and caveats or full-scale architectural simulation research it is necessary to scrutinize the purposes of full-scale simulation and how major impact of virtual technologies affect them.

Old Questions

Before the advent of virtual technologies, it was feasible to ask *"What can a full-scale mockup do that scale models and drawings cannot do?"* When drawings and scale models were no longer enough, the next step was simply to build full-scale mockups in the normal course of developing a space habitat project and then to ask:
"How do we evaluate it?" and *"What did we learn from building it?"*

New Questions

However, the developments in virtual technology provide alternatives to some former needs for mockups, and so design researchers must ask a sharper set of questions before going the difficulty and expense of building a full-scale artificial environment. question different question: *"What do we need to learn or to demonstrate? When do we need to build something full-scale to do it? how can we predict what we will learn or even what we need to learn? What can we learn from full-scale architectural simulation that we cannot learn from CAD or other virtual technologies?"* The conclusion of this paper attempts to answer this set of question as a general benchmark for when to develop full-scale architectural simulation.

This pair of questions of ***need to know*** and ***need to build*** signifies an improvement over the "build it to demonstrate the concept" approach that traditionally underlay most mockups. But these two issues are still problematic for architectural simulation research. When undertaking full-scale design research, there is a large measure of serendipity involved and we cannot know in advance what we will learn, or what we want to learn, nor can we rely entirely on what we believe initially that we need to learn.

The Five Purposes

In confronting this dilemma, it becomes necessary to examine the various purposes for which architects, engineers, industrial designers and scientists utilize full-scale simulations. The common objective of all these kinds of simulation is to model or try to predict in some what people will do or must do in "future worlds" (Clipson, 1988). These simulations can vary considerably, not only in permanence and expense, but also in purpose at the level of cause and effect. Within this scope there are five purposes of full-scale simulation experimental simulation, mission preparation and training, demonstration and communication, hardware integration testbed and engineering production mockup. These five purposes are ordered on a spectrum from the most experimental to the most manufacturing-oriented. All of these variants on full-scale simulation are mission-specific to some degree, but they may also be flexibly applicable to a number of different missions or even vehicles.

Experimental Simulation involves simulation for purposes of scientific inquiry into human performance. Example Ames Research Center Man-Vehicle System Research Facility 727 and Advanced Cab cockpit simulators. These research simulators serve a purpose that is distinct from general purpose training simulators that provide training and proficiency updates to pilots.

Mission Preparation / Training Mockups serves to develop special skills and problem–solving for specific missions, often in extreme environments. Examples of mission preparation and training include the neutral buoyancy testing for extravehicular activities conducted in underwater facilities at several NASA centers. For oil drilling platform work, the Oceaneering Corporation builds detailed mockups for their divers to practice all tasks before going into the ocean to perform the work. These mockups also are distinct from general proficiency trainers. The space shuttle trainers at Johnson Space Center provide some general proficiency training, but their primary role is for specific mission preparation training.

Demonstration / Communication Mockups serve to convey ideas at a large scale, particularly for new design proposals and concepts. The marketing aspect of this species of full-scale simulation will probably suffer the greatest inroads from virtual technologies as everyone from engineering firms to kitchen cabinet refinishers cash in on this marvelous new sales tool. However, in the realm of complex technology integration for simulating group operations purposes, the full-scale demonstration simulation will remain a viable and essential tool. Most space station mockups to date fall into this category. The Human Exploration Demonstration Project has one foot in the demonstration domain and another in the hardware integrated testbed domain.

Hardware Integration Testbeds provide a functional simulation of actual prototype hardware in a breadboard-like setting in which diverse components and functions work together. Hardware integration testbeds that do not require direct human integration are common both within NASA and many industries. However, when a full-scale architectural simulation incorporates the attributes of a hardware integration testbed, direct human involvement or integration in the operation, testing and evaluation of the testbed becomes essential. Examples of these kinds of testbeds include the Life Support Testbed at NASA- Marshall Space Flight Center and the Human Exploration Demonstration Project currently under development at NASA-Ames Research Center.

Engineering Production Mockups are primarily manufacturing tools for putting together very complex assemblies. Full-scale production mockups have traditionally been a necessary step in both the aircraft and submarine manufacturing industries. In these mockups, a complete, highly detailed model of the final product includes all the actual hardware prototypes or physical representations of that hardware as a master key to assembling the product on the shop floor. The Skylab Engineering mockup at Marshall Space Flight Center served as both a hardware integration testbed and an engineering production mockup, as well as a mission trainer. However, the application of full-scale mockups purely for engineering productions mockups may disappear, as it did for the Boeing 777.

Control versus Realism

Space missions pose a special need for full-scale simulations that serve multiple purposes as the Skylab mockup did. Connors, Harrison and Akins observe:

> Mission Simulators . . .are particularly important in space mission design because there is essentially no opportunity for a graduated series of practice efforts under true operational conditions before the mission takes place. Since space mission crews must be trained and highly proficient in their tasks before the flight, it is imperative that high-fidelity simulator systems be available for training on specific, individual aspects of the mission (partial simulation) and for the completely integrated "dress rehearsal" simulation of the mission (full-scale simulation). [Connors, Harrison & Akins, 1985, p. 115].

This observation about partial and full mission simulation raises a second set of questions about full-scale simulation, on the spectrum of control versus realism. Classically, there are trade-offs between control and realism, which vary inversely in most fields of human performance research. The same condition holds for architectural research, but also correlate to the way in which an architect conducts design research as a component of professional practice. The three classic categories of research; basic, applied and field relate to architectural research on a somewhat broader scale than just full-scale simulation, but still apply equally well.

Basic Research

Basic research usually involves limited realism with a high degree of control, such as is often conducted in a laboratory. Basic research in architectural design involves ideal, paradigmatic, unconstrained design, as is typically performed in the studio. In this context, Walter Gropius described the studio/workshops of the Bauhaus school of design as laboratories [Gropius, 1965, p.53].

Applied Research

Applied research usually involves a dynamic trade-off between realism and control, in which the researcher may weight the scale one way or the other depending upon the needs of the investigation. Applied research in architectural design involves Prototype or Demonstration Design and parametric investigation of the necessary performance characteristics of an environment or product.

Field Research

Field research is usually the most naturalistic approach, in which control is very limited but there is a high or total degree of realism. In architectural design research, professional practice generally falls within the realm of field research or design consulting. Christopher Alexander's epic work Pattern Language, exemplifies one approach to field research in architecture.

Fidelity

The degree of fidelity of a full-scale simulation can vary considerably and can have a complicated effect on the overall simulation. Although classically, increasing realism in most experiments decreases control correspondingly, increasing realism through higher fidelity does not translate into less control. But neither do changes in fidelity increase the level of control, so that sometimes changes in fidelity or an inconsistency in the degree of fidelity throughout the artificial environment may act as a disturbing variable.

Correlation of the Spectra

In order to fully appreciate the interaction of research purposes with research controls or the lack of them, it is valuable to intersect the Architectural Simulation Purposes Spectrum and the Control Vs Realism Spectrum. Figure 1 illustrates the principal domain of architectural design research within these biaxial spectra. Note that this domain falls most solidly in the center of the chart and that the corner conditions of experimental/basic, experimental/ field, manufacturing/basic and manufacturing/field intersect it only tangentially.

Architectural Simulations

For purposes of illustration of how these spectra, it is useful to locate for specific examples of recent and future full-scale simulation on this chart. The Space Human Factors Office at NASA-Ames Research Center developed three of these simulations for Space Station Freedom: ***Space Station Proximity Operations Simulator*** (1985–89), ***Space Station Wardroom Mockup*,** (in cooperation with the Southern California Institute of Architecture, Santa Monica and Future Systems, Inc. 1987–88) and the ***Element Control Work Station*** for the Space Station United States Laboratory Module Mockup, (in collaboration with the Man–System Integration Branch, NASA–Marshall Space Flight Center, 1987–90). The Human Exploration Demonstration Project is a multidisciplinary simulation of a lunar or planetary base, or a Mars transit vehicle, involving the four disciplines Life Sciences, Life Support, Human Factors and Automation Science.

Figure 2 locates these four projects on the biaxial spectra. Figure 3 shows these four exemplars in the context of a number of other kinds of full-scale simulations across a broader spectrum.

1. Space Station Proximity Operations Simulator, 1986–89

Space Human Factors Office, NASA–Ames Research Center

What is the interaction of a window / work station with flight operations?

• Proximity Operations Mockup and Experimental Simulator

• Optimal oblate ellipsoidal geometry with off–center port that separates circulation from critical circulation and preserves meridian shell stresses.

• "Keystone" window geometries that integrate with computer graphics.

• Perspective display to show relative positions and vectors of spacecraft

• Shuttle certified side–arm controller for realistic computer graphic input

• Voice recognition checklist system leaves the hands and eyes free.

2. Space Station Wardroom Mockup, 1987–88

Southern California Institute of Architecture, Santa Monica and
Space Human Factors Office, NASA–Ames

How to design a wardroom that accommodates eating and gathering for a crew of 4 to 8 plus a large range of "associated" living and working activities?

• Deployable and adjustable table expands from four (compact position) to eight (deployed position) diners.

• Deployment of additional leaves for the second four diners for only would not be acceptable because it would create "in" and "out" groups so expansion of the compact surfaces was also necessary.

• The table can function also as an adjustable work station for the crew.

• Wardroom windows must accommodate both the lowered zero G neutral body posture sightlines and viewing the earth, so windows can be located in the lower 45° sectors of each side of the module.

• Exercise equipment may be stowable or enclosed in demountable fabric structures within the module.

• The sense of ceiling height is vital to creating a perception of spaciousness — rotating the module 45° allows a standoff longeron to be removed to create that "loft."

3. Space Station U.S. Laboratory Module Mockup, 1987–90

Man–System Integration Branch, NASA–Marshall Space Flight Center and
Space Human Factors Office, NASA–Ames

Components:

- Mockup of physical size, structure, organization and appearance of Space Station laboratory racks in a cylindrical shell. (C Fidelity)

How to use illumination efficiently while providing spatial orientation ?

- **Lighting design with up/down differential.**
  - Wash the rack faces with even illumination.
  - Provide visual cue to local vertical by making brighter illumination "up."

How to design a workstation in a single rack that supports the activities of 3 crewmembers for the critical functions of operating the lab module?

- **Element Control Work Station. (C Fidelity)**
  - The essential communications function: videoconference facility for discussions with researchers on the ground.
  - Provide an "Office" to 3 Lab crewmembers from which they can control their own schedules and work together.
  - Provide an arrangement of displays that responds to the organization of work in the lab module.
  - Multiplex information handling is key, indicating a video matrix switcher and screen videoplexer.

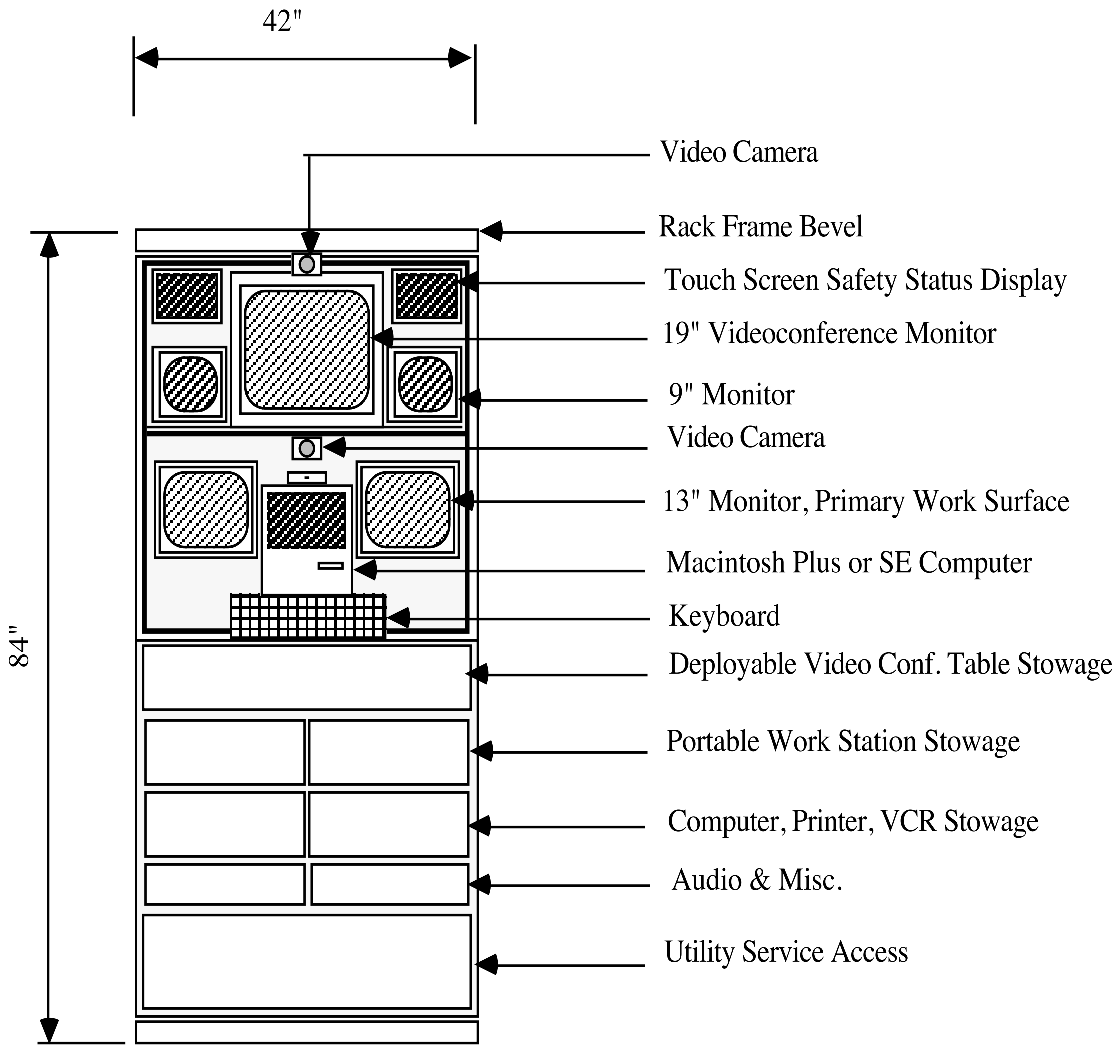


Figure 4. Element Control Work Station Schematic Elevation.

Diagram of Element Control Work Station in US Lab Mockup

How to support 3 crewmembers for videoconference "Office hours" and planning sessions in Zero–gravity?

- **Deployable Video Conference Table (A/B Fidelity)**
    - Provide ergonomic arrangement for 3 crewmembers to conduct working videoconferences with the ground.
    - Stow compactly in the rack.
    - Deploy easily and be highly adjustable for Zero–G.

•Need a deployment mechanism that can expand beyond the width of the rack and allow extensive adjustment.

Conclusion:
Responses to the New Questions about Full-scale Simulation

What do we need to learn?

How people interact with the designed environment in complex and demanding living and working situations.

The properties of the designed environment that we do not understand.

What can we learn from full-scale architectural simulation that we cannot learn from CAD or virtual reality?

How humans, especially in groups, respond and perform in a complex information and multiple task environments and scenarios.

How the physical environment itself performs.

When do we need to build something full-scale to learn it?

Part–task laboratory simulation is inadequate for complex task handling or physical attributes are critical to human performance.

We need empirical verification of computational predictions.

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