Adaptive Autonomous Performance in a Sensitive and Integrative System (AAPSIS) for a Telemedicine Unit

Álvaro Malo
Professor of Architecture
Emerging Material Technologies in Architecture, University of Arizona

Native American populations have urgent need and limited access to health care. The University of Arizona's Telemedicine program is an efficient means of delivering clinical, diagnostic and continuing education for the Indian Health Services system. To date, over 1,000,000 teleconsultations have been conducted resulting in enhanced clinical care for Arizona's population. However, the current telemedicine systems lack facilities that can adapt to variable physiographical settings and functional needs, that are culturally competent and user-friendly, and that have sufficient autonomy in off-grid remote locations. The goals and challenges of the proposed research will focus on the integrative design and realization of an efficient and competent Telemedicine Unit that will require the following attributes: (1) Adaptive to variable programmatic needs, climatic conditions, and cultural settings; (2) Autonomous, self-sufficient of energy and resources in off-grid remote locations; (3) Sensitive to human physiology, material propensities, and environmental factors; (4) Integrative of aesthetic socio-cultural, and ecological systems; and, (5) Sustainable prospect of use and regeneration of natural resources : air, water, light, energy and land. The Telemedicine Unit will be located in Sells, Pima County, AZ., The research and design process will be carried out with the integral participation of the Tohono O'odham Nation (TON) and the Tucson Area Indian Health Services (IHS).

The objective of the proposed research is to develop the fundamental scientific, engineering, technical, aesthetic, social and cultural principles required to initiate a paradigm shift in the design, development and operation of energy/resource efficient and sensitive sustainable buildings. We propose the development of advanced and innovative concepts, which using interactive modeling and simulation, apply fundamental scientific and technical principles in the architectural design, engineering, testing, and construction of a Telemedicine Unit. This transformative paradigm is based on an efficient and graceful interface between buildings as operating "hardware" and human beings as sensible, sensitive, and culturally evolving "software." Cultural competence of this facility requires that special attention be paid to both the performance of clinical functions as well as to integrative aesthetic perceptual feedback loops. Integrative aesthetics includes measurable human sensory responses related to the buildings environmental conditions, which affect human comfort and well being and provide the common sense of an immanent aesthetic.

The proposed research introduces a new paradigm in built environments: autonomous, sustainable, adaptive and sensitive building. The research on pneumatic envelopes with automorphic and phototropic properties will provide key insights into the engineering, technical and materials aspects of adaptive building. Insight gained from the study of energy production and energy storage by integrating flexible photovoltaic cells and compressed air storage within the building envelope will help establish the principle of *autonomy*. Thus, we will explore the application of high efficiency dual use compressor/motor systems in enabling operation of the unit as well as for energy storage and recovery. The integration of new micro and macro sensor technologies into the building that can respond to environmental, structural and human factors will enable the design of a *sensitive* building. The development of model-based *multi-paradigm simulations* for real-time management of the complex interactions between flow of resources and human occupant establishes the foundation for *integrative modeling* of architectural design, engineering systems, operational building needs, human physiological and psychological comfort, and cultural sensitivity.

A. VISION AND GOALS: We propose the development of advanced and innovative concepts, which using modeling and simulation interactive environments, apply fundamental scientific and technical principles in the architectural design, engineering, testing, and construction of a Telemedicine Unit (TMU). This transformative paradigm must be based on an efficient and graceful interface between buildings as operating "hardware" and human beings as sensible, sensitive, and culturally evolving "software." Cultural sensitivity toward users (patients) of this facility requires that special attention be paid to both the performance of clinical functions as well as to integrative aesthetic perceptual feedback loops. Integrative aesthetics includes measurable human sensory responses related to the buildings environmental conditions that affect human comfort and well being and that provide the common sense of an immanent aesthetic. More specifically, we envision a building-environment system that possesses the following attributes:

- Adaptive to variable programmatic needs, climatic conditions, and cultural settings
- Autonomous, self-sufficient of energy and resources in off-grid remote locations
- Performative efficiency regarding daylight, acoustics, energy balance and building physics
- Sensitive to human physiology, material propensities, and environmental factors
- Integrative of aesthetic (i.e. visual, acoustic, thermal, haptic, ergonomic, etc.), socio-cultural, and ecological systems
- Systematic thermodynamic prospect of use and regeneration of natural resources (i.e. air, water, light, energy, land, etc.)

Specific research goals will include:

1. Discovery of a science and technology of adaptive sustainable buildings with dynamic morphing properties (e.g. automorphic structure, phototropic envelope, ergonomic adaptation).
2. Integration of new sensor technologies responsive to environmental factors, structural adaptation, and human physiology and behavior.
3. Creation of virtual environments for modeling and simulation of human responses to sensory stimuli in adaptive spatial environments.
4. Development of a model-based computational control system for real-time management of the complex interactions between flow of renewable resources and human occupant needs in adaptive structures
5. Establishment of architectural design and engineering principles derived from a scientific understanding of the operational energy needs of the building and the thermodynamic thresholds of human physiological comfort
6. Fine tuning of adaptive material spatial morphologies responsive to perceptual well being.

B. APPROACH AND METHODOLOGY: The proposed research program is described schematically in the flow chart shown below (Fig. 1):

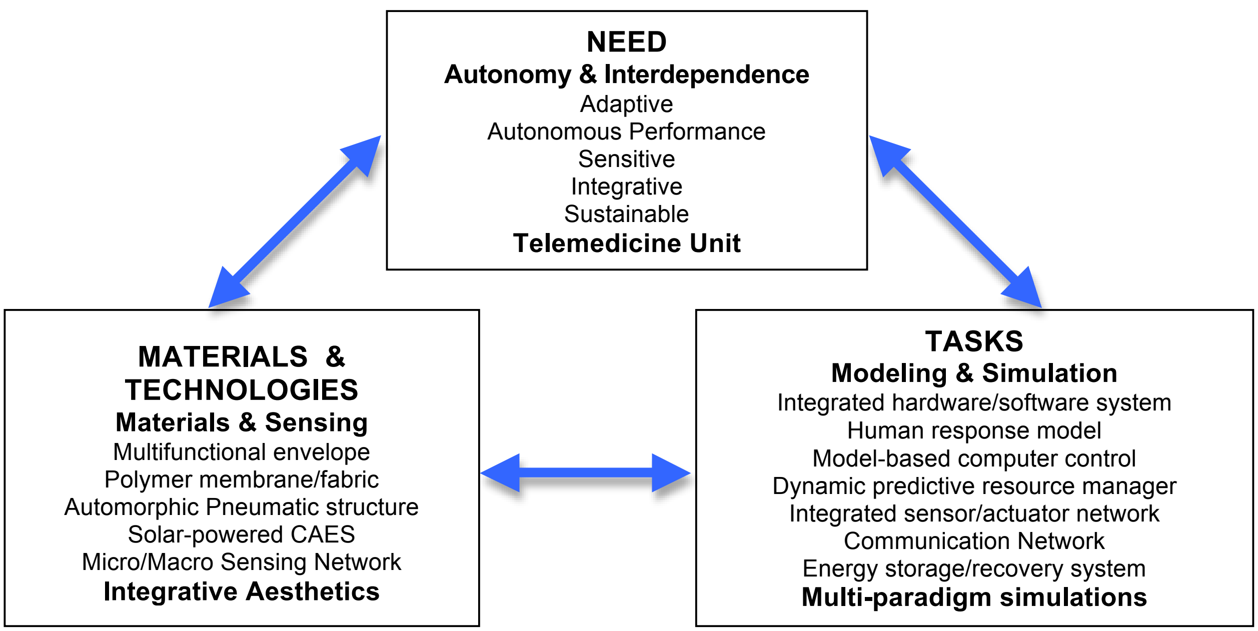

Figure 1: Flow chart of new paradigm systematic relationships between Needs, Tasks, and Material Technologies.

The clinical staff identified the following Tele-health program needs as having the most significant impact on their day-to-day care of the patient population:

- Tele-Cardiology, providing real-time ECHO and Ultrasound
- Tele-Pain Clinic, providing pain management consultations
- Tele-Health educational programs (HHS/IHS or CDC community programs, Arizona Dept of Health collaborative programs, U of A grand rounds)
- Tele-Psychology, providing live family or personal behavioral consultations
- Tele-Dermatology, providing store and forward or live dermatology consultations
- Tele-Rheumatology, providing the patients with increased real time rheumatology consultations

The design attributes of the proposed telemedicine unit that will meet the needs of the Telemedicine program and the Tohono O'odham nation are presented in Figure 2.

Design Attributes / Needs & Requirements	Pneumatic Building Envelope	Adaptive Morphology	Sensing	Compressed Air Energy Storage	Autonomy	Integrative Modeling System
Cultural competence and user comfort		O	O			O
Adaptive functional space	O	O				
Operation power 6-7kW			O	O		O
Off-grid				O	O	O
Mobility	O				O	
Ease of deployment	O				O	
Minimum site impact	O				O	
Low systemic ecological impact	O	O	O	O	O	O

Figure 2: Table showing correspondences between Needs & Requirements and Design Attributes.

C. SPECIFIC RESEARCH PLAN: To meet the objectives of this project we will take an approach in the design of the building system that addresses several integrated functionalities. The multifunctional envelope will provide efficient energy harvesting, energy and water storage capacity, thermal storage and insulation, as well as light transmission. This envelope will be endowed with automorphic and phototropic properties to optimize its functions by adapting to environmental cyclic changes and human needs. To achieve theses functionalities, we will take advantage of technological progresses in new synthetic materials, pneumatic envelop design and microsensor technologies. We will investigate pneumatic phototropic envelopes composed of three-layered partitioned membrane systems to meet daylight, acoustics, energy balance and building physics requirements. The supporting infrastructure will incorporate materials with energetic and structural attributes, such as: (1) Flexible FRP tubing for air circulation system; (2) Flexible shielded FRP tubing for power supply system; (3) High modulus FRP for compressed air storage; and (4) Recyclable thermoplastics for water storage and circulation systems.

1. Building envelope: The choice of a multifunctional pneumatic envelope is highly compatible with the proposed Compressed Air Energy Storage (CAES) and management system, with light-weight and mobility which are consistent with the principle of autonomy, and it will require minimum site preparation for easy deployment in cases of emergency and natural disasters.
The pneumatic building envelope will be composed of a multifunctional three-layer membrane system:

- **Outer layer**, consisting of PTFE (polytetrafluoroethylene) coated glass fabric cells inflatable to 30 psi (2atm). Cells are basic elements of all systems in living nature; intensive research programs on cell-based pneumatic structures have been developing in the past 15 years in academic and industrial settings [Hensel, Menges and Weinstock, 2010]. The PTFE membrane is chosen for its high tensile strength, resistance to abrasion, atmospheric aging, corrosion and fire—it is also chemically inert. A modular array of Photovoltaic PV-Flex film will be overlaid, or encapsulated, in the PTFE fabric’s southern surfaces to maximize direct incident sunlight exposure and energy generation.
- **Middle layer**, consisting of structural Kevlar reinforced tubing inflatable to 120 psi (8atm). These will be arranged on a dual-lattice to provide structural redundancy (for security) and anisotropic orientation to control morphological adaptation by pressure differential. A secondary distributed pattern of carbon fiber stays and Kevlar tendons will be considered for additional control and balance of the structural system's flexibility and stiffness.
- **Inner layer**, consisting of sound absorbing (70%NRC), low E (infrared) coated fabric with defined light transmission and acoustical properties. This layer will be sensitive and

responsive to physiological aspects of human comfort, cultural competence and integrative aesthetics: visual, acoustic, haptic and other sensorial properties—which may be capable of systematic fine-tuning. In addition, this layer will operable and manipulable directly by the users by low-tech means.

The envelope will be partitioned into individually inflatable cells that will enable it to morph (eventually automorphing via intelligent control software) and function in response to local conditions through sensing of light, pressure, and temperature. The partitioning into cells will provide a high level of stability and fault tolerance. Each pillow will contain a low-cost pressure sensor/actuator pair and a simple communication mechanism responsible for assessing the state of its neighbors [Enikov and Lazarov, 2003]. The response of each pillow will be controlled by a low-cost sensor/actuator printed or woven into the fabric. The principle of emergent behavior will be utilized to control the shape and function of the inflatable surface. Resultant effects include minimizing or maximizing the solar gain by local regulation of pressure in the inflated pillow leading to change in the shape of the building envelope. Similarly, regulation of light intensity inside the building will be controlled by the response of an array of autonomous apertures integrated into each pillow of the fabric. Communication between neighboring cells could be wired or wireless. Commercial solutions include using a 1-wire interface circuit as a means to serially transfer data between multiple slave nodes (sensors) and a data-logging device (master). The protocol allows a large number of sensing nodes to be attached to a single wire, which is also used to provide power to them. An alternative solution is the use of low-frequency wireless communication akin to the RFID tag technology that allows passive operation, i.e. the transponding sensor is powered by the electromagnetic field of the transmitter/receiver. Since selecting the size and power of the two coils can control the range of transmission, it is possible to fabricate transmitter/transponder pairs that operate locally between two adjacent cells, thus avoiding collision between multiple sensors. Finally, interior retractable layered partitioning will be endowed with thermal, acoustic and haptic functions using porous, air and water filled composite acoustic materials.

2. Sensing: Integrated sensors for pressure, strain, temperature, humidity, and carbon dioxide content are key to providing the adaptive function of the telemedicine unit. Additionally, a large number of low-cost wireless pressure and strain sensors integrated into the building envelope are needed in order to provide feedback from each of the pneumatic compartments comprising the envelope. Under this task, we will develop a low-cost integrated sensing module based on wireless radio frequency identification technology (RFID).

- **Embedded strain gauges for control of pneumatic inflation:** Traditional strain gauges are based on thin metal foil attached to a polymeric substrate that is subsequently bonded to the structural element whose deflection is being monitored. This type of strain gauge is particularly suitable for integration into the building envelope since it can be directly spliced onto the pneumatic cells.
- **Pressure Sensor:** Pressure sensors are now well-established tools in life-science automation. Most pressure sensors utilize a deformable membrane with integrated strain- or displacement-sensing elements.
- **Humidity Sensor:** In humidity measurement (hygrometry), it is common to measure one of several interrelated parameters: relative humidity, water vapor pressure and the dew point temperature.
- **Temperature Sensor:** Temperature sensing is a mature field within the sensor industry. The most commonly devices are thermocouples (TC-s), resistance temperature detectors (RTD-s), thermistors, and diode temperature sensors.
- **Carbon Dioxide Sensor:** Traditionally, measurements of CO_2 are based on the use of an aqueous solution in contact with the unknown sample. Since CO_2 reacts with water to produce carbonic acid, the pH of the aqueous solution can be used to measure the amount of CO_2.

3. Energy storage and management: The proposed off-grid telemedicine unit will utilize solar energy as its primary source of energy. Solar is the largest energy resource in Arizona and it can provide clean and sustainable energy. With an estimated surface area optimally exposed to sunlight of approximately 100m^2, the envelope will have a targeted power production of approximately 10kW (considering a conservative estimate of flexible PV efficiency of 10%). However, solar energy is intermittent, and as such, it often cannot provide temporally consistent electricity. Furthermore, energy supply (sunshine) and energy demand do not match temporally, and the matching gap changes with seasons, Effective energy storage solutions need to be developed to supply consistent power and meet the variable energy demand of the TMU.

Some of the most established energy storage methods include compressed air, thermal storage and batteries, each offering unique ranges of response time, capacity, charge time, efficiency, uncertainty behavior, and cost. Compressed air energy storage (CAES) is a mature technology and offers design flexibility and low carbon footprint. CAES is an *environmentally benign storage solution* that is geographically unconstrained.

The CAES system will include a variety of components, namely high efficiency compressor modules, storage units, and energy compressed air motors/turbines for energy recovery. The compressor system will be readily scalable to operate and power the telemedicine unit by association of several modules in parallel or in series. The compressor prototype will be designed to operate as an open compression cycle system under isothermal conditions, carried out in a slow quasi-static fashion, thereby greatly reducing power consumption during compression — as compared to standard industrial air-compressors that function under adiabatic conditions [Lemofouet-Gatsi, 2006]. A low-cost, environmentally benign modular compressor unit, which can be used in conjunction with off-grid stand-alone photovoltaic cells, has already been built and tested.

4. Integrative Modeling System:

The proposed energy storage will be part of a complex system that includes energy production and energy demand. This system involves a multiplicity of temporal scales and a variety of energy capacity, storage technologies and scales. Thus, efficient storage and energy recovery calls for a systems approach to its design and operation that accounts for all the complex interactions between energy demand, solar energy supply, energy storage technologies and factors affecting the interactions such as weather changes, season changes.

As part of the integrated software system that will drive the telemedicine unit, we propose to design an optimization model to manage PV energy supply, to control storage of energy, decide what type of storage technologies to be used and at what scale (e.g. compressed air, thermal, or electrochemical), in response to energy production and demand. The model will consider the capacity, response time and efficiency of the various storage and energy recovery systems.

In this work, we propose a data driven, simulation-based planning and control approach as the basis for the management framework to optimize energy usage based on existing and predicted resource availability and usage requirements. In the planning phase, the simulation evaluates different control policies to govern the energy system (generators, storage units, appliances, and water systems) based on the current sensor readings (e.g. generation; weather information; demand).

Hardware-software feedback monitoring disjunctions and/or synergies between human activity and building mimesis will be accomplished via multi-paradigm simulation methodologies (system dynamic, agent-based model, dynamic system). In particular, a system dynamic model will be developed to represent an environment (solar irradiance, cloud pattern, pressure, temperature, humidity, among others). Agent-based models will be developed to represent culture-specific human responses (involving synthetic cognitive model) as well as the proposed automorphic partitioned building envelope.

From early programming to post occupancy evaluation Building Information Models (BIM) will enable us to actualize a more robust paradigm based on collaboration and transparency. The sharing of increased amounts of information will allow effective communication to a large design team: architects, engineers and consultants, but also incorporating manufacturers, contractors and sub-contractors into the process to create more integration with the final output. Digital models will facilitate our iterative prototyping/CNC fabrication process. The models will also provide the ability to analyze a building according to its systems: climate, structure, skin, services and assembly techniques. The design model will be focused on making sure that performance is optimized technically. Iterative models can be budgeted accordingly: recognizing the importance of addressing maintenance and repair costs, thermal insulation properties and life expectancy.

5. Cultural Competence and User Comfort: From a human occupant point of view, the telemedicine unit serves three functions:

1. Bringing health care to people in remote communities, specifically those living on reservation land in Arizona.
2. Teaching Native American (NA) people to serve as technical staff, thereby bringing technical knowledge and jobs to those in remote communities.
3. Interacting with those in remote communities to determine how best to maintain their long-term health.

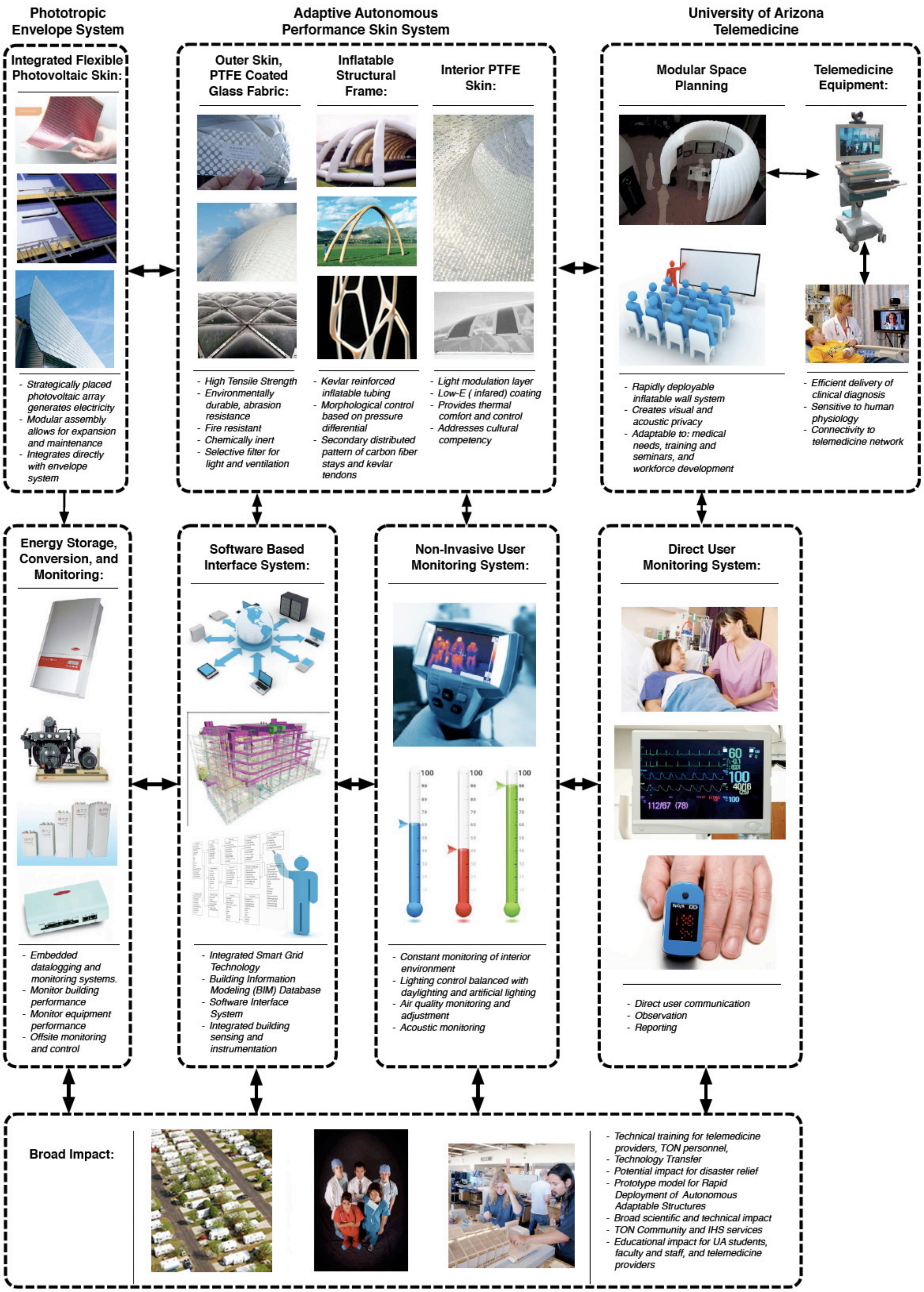

Figure 3: Diagram of System Components and Integrative Modeling

D. SCHEDULING OF TASKS AND COMPONENTS

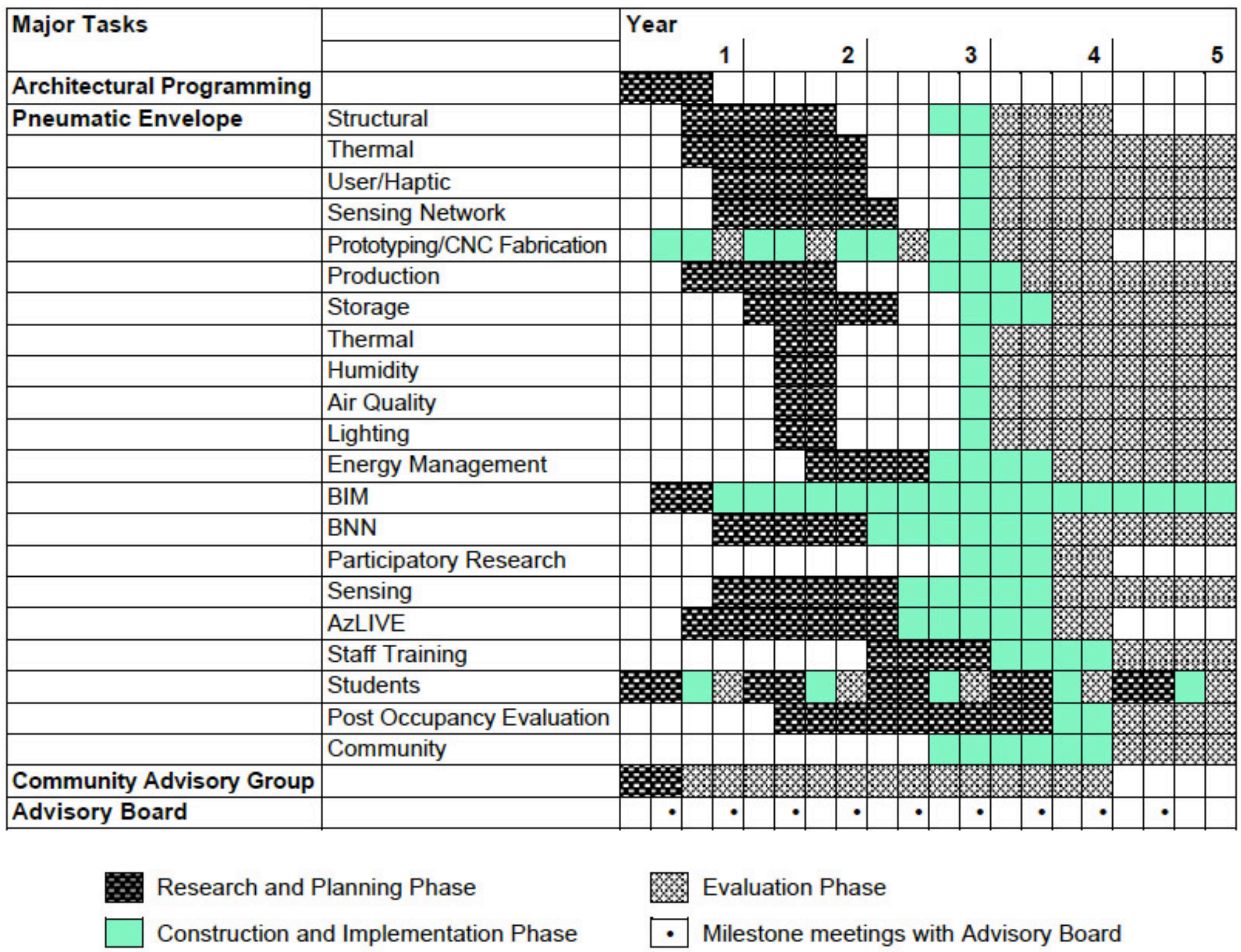

Figure 4: Scheduling of Tasks and Components

E. KEY PERSONNEL

Name	Department, School or College	Expertise
E. Brody	Medicine	Clinical Services/Native American Cardiology
P.A. Deymier	Sustainable Engineered Systems	Materials, Energy Storage, Sustainability
S. Dickinson	Architecture	Building Information Modeling (BIM)
E. Enikov	Aero. Mechanical Engineering	Sensors and sensor networks
A.M. López	Medicine	Telemedicine
Á. Malo	Architecture	Emerging Materials Technologies in Architecture
M. A. Peterson	Psychology, Cognitive Science	Cognition and Neural Systems
Y.J. Son	Systems Industrial Engineering	Model-based multiparadigm simulations

Figure 5: Key Personnel

F. ORGANIZATION AND MANAGEMENT

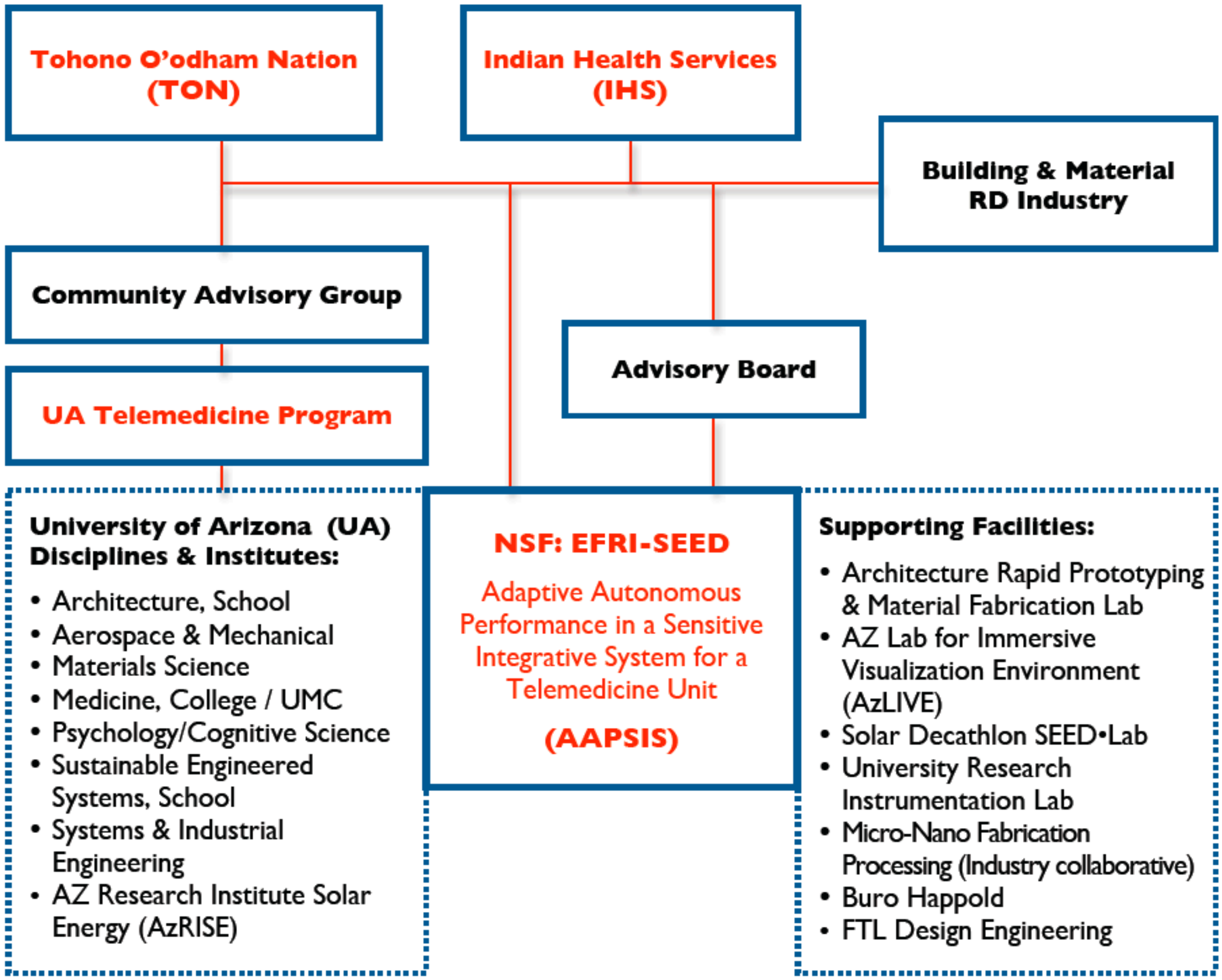

Figure 6: Organization and Management flow-chart