INSPIRE Letter of Intent Supplemental Form
(to be e-mailed as an attachment to inspire@nsf.gov; LOI ID in Subject field)
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LOI ID (*enter 8 digits in place of ########*): L02382755

INSPIRE Track *(enter* 1 *or* 2 *in place of #):* 2

Project Title: Integrated Design of Energy-efficient Adaptive Living Structures (IDEALS)

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Supplemental Information about the project, adding to (not duplicating) the FastLane LOI *(limited to 10,000 characters for Track 1; limited to 15,000 characters for Track 2; tables, figures, etc., count toward these limits in accordance with the space that they fill):*

- **Intellectual Merit (general comments):**

Reconfigurable walls, ceilings and ducting can ***radically*** transform buildings from being ***fixed*** and ***static***, where each building is designed solely for a specific purpose, to ***adaptive*** and ***living.*** The IDEALS project proposes an adapto-building, one that can be, through appropriate control, dynamically reconfigured in response to outside conditions as well as the use to which it is put, the goal being energy minimization and greater sustainability. There are three time scales for adapto-building dynamics: (a) short term to respond to outside temperature changes that occur within a daily cycle, (b) medium term to respond to yearly seasonal changes and environmental conditions which may be different from year to year, and (c) long term alterations due to changes in building utilization. Reconfiguration specifically means the following: relocation of walls or ceilings, heating, cooling and ventilating ducts, and reorientation of the whole building. This will be done using electric motors responding to control signals from a computer, so in that sense the process will be adaptive. Though the principle of reconfigurability is easy to understand, it needs to be shown not only that it can work in practice but also that there are significant benefits to doing so. Dynamic reconfiguration provides a way to both minimize energy and maximize sustainability. Success in this will lead ultimately to the development of design procedures for larger adapto-systems.

One of the products of IDEALS will be a laboratory-scale model to test aspects of adapto-design principles. These laboratory experiments are a necessary precursor to future field tests. The second outcome will be a verified and validated computer program that will simulate the laboratory model and its changing conditions. This code will then be used to predict how different designs and adaptations of a full-scale adapto-building will affect its performance. The third result will be an integrated design methodology, including analysis from all disciplines. A software package to facilitate design will be developed which will be made freely available.

To make adapto-design possible the following aspects of the problem have to be considered in an integrated fashion.

Structural: The construction will have to be structurally stable and able, through suitable electric motors, to move and adapt as dictated by the control logic. From a structural perspective, the intellectual merit of the proposed research lies in finding novel solutions for load paths, while ensuring redundancy, within the context of reconfigurable walls and ceilings. The simplest structural design—a box that supports cantilevered movable floors with non-load bearing movable walls—may not be the most sustainable design since this structural system is not the most efficient way to carry loads and would ultimately lead to large members that contribute to a high embodied energy. Furthermore, if all floors and walls move, the installation of utilities like heating, cooling, water, and electricity, may be prohibitively difficult. Instead, an interdisciplinary design approach will be developed which includes a combination of fixed load-bearing paths, which could also include critical utilities, combined with reconfigurable walls and floors that are not structurally required.

Control: The control strategy, the brains of an adapto-building, will be responsible for meeting the energy-minimization and sustainability-maximization goals. The control system will receive data on exterior and interior conditions—such as temperatures and flow velocity—as input and will provide commands to the electric motors for the actuation of walls, ceiling, and ducts. A model predictive approach based on computations will be adopted: numerical computations will be used to make predictions, and actuator signals will be based on these predictions. Multi-roomed structures, such as office buildings, generally operate on a multi-zonal basis, and that technique will be applied as the algorithms are scaled up from the laboratory experiments to larger adapto-buildings.

Computational: Computer simulation will be used to test the structural stability of the laboratory model. Experimental data will be used to update boundary conditions on the mathematical model on which the simulation is based. The model predictive control strategy will base itself on predictions made by simulation. Thus the computation has to provide reasonably accurate real-time representation of the flow and heat transfer within the experimental model. Convection inside rooms is generally of the mixed type with a Rayleigh number that can be as large as 10^{11} or 10^{12}. Hence turbulence modeling, boundary layer flows and thermal stratification will have to be taken into account by the computations. The simulations will be carried out at two levels: a detailed first-principles mathematical model will enable convective heat transfer coefficients to be determined that can then be used in a lumped model for real-time control.

Experimental: There are two purposes to the experimentation: one is to provide information for the simulation and the other is to test its predictions and those of the control strategy. The structural ability of the walls, ceiling and ducts to move will also be verified and validated in the laboratory-scale model. Measurement and control will be through sensors that measure local temperature and air velocity, and a large number of these will be located throughout the model. Actuators to heat, cool and ventilate will also be placed on the periphery; the temperatures and flow rates will be determined by heaters, coolers and dampers in the inlet ducts. Some of the sensor outputs will be fed into the control computer, which will then command the actuators. Data transfer will be through battery-operated wireless devices that will form a robust communication network to provide connectivity in the face of reconfiguration and node failures.

Sustainability of Use: The failure of a building to remain useful and efficient over time significantly influences the sustainability of that building, and, ultimately, contributes to the growing issue of energy and resource waste in the built environment. Given the premise that unresponsive, single-use structures are unsustainable, in terms of energy use in operation and energy and materials involved in construction (and demolition) processes, structures that are responsive to dynamic external conditions (climate and weather) and variable interior conditions (in terms of function) will achieve a greater sustainability of use over time. A sustainability of use measure will be developed to predict the associated "costs" of the kind of multi-system/multi-scale building adaptation proposed here as compared to customary static building adaptation strategies. A quantitative matrix-based measure will be developed to compare the cost of energy used for the initial construction, the operating power cost, and associated reconfiguration impacts when a space or series of spaces is reconfigured to an alternate use. From this matrix, different configuration thresholds can be determined and modeled, from which a guide of best design practices for IDEALS structures can emerge.

- **Identify and justify how the project is interdisciplinary.**

The various engineering disciplines and architecture have grown increasingly specialized–each offering its own silo of expertise that is optimized based on field-specific priorities. However, for the design of sustainable buildings, individually optimized solutions do not necessarily lead to an optimal building, and a multi-objective and multi-discipline approach must be considered. For example, an elegant architectural concept does not necessarily lead to an efficient structural form; box-like rooms that simplify structural analysis do not necessarily result in spaces that optimize the flow of hot or cool air. Rather, it is at the intersection of disciplines that an adapto-building design can be found. IDEALS will integrate mechanical, thermal, controls, and structural engineering with architecture to produce the transformative technologies necessary for sustainable adapto-design. The team includes PIs and students from each field who will work together. The post-doc and many of the graduate students in this research will be co-advised. The interdisciplinary team of PIs consists of four engineers (one electrical, one civil and two mechanicals) and an architect.

Examples of the cross-cutting nature of the technologies proposed here are the following. The structural design must be compatible with the motion of walls, ceiling, heating and cooling ducts; the control strategy must take into account numerical simulation of mixed convection in the rooms and local air velocities; the sustainability of use measure must consider the whole building and also be subject to its constraints; the experiments and the computation must interact with the structural engineering and the control system, and with each other. In sum, few of the features of adapto-design can be developed without relating it to the others.

- **Identify and justify what is potentially transformative in the project.**

Brick and mortar buildings have limited adaptability in terms of use and environmental control. Customarily, buildings are constructed to serve a single, known function (and therefore occupancy group), wherein the walls and building services are largely fixed in place until it is substantially altered or ultimately demolished. As the weather and the seasons change around a fixed structure, and user preferences vary within it, a traditional building will employ a (typically energy-intensive) control system for heating, cooling and ventilation to provide physical comfort for the people within and/or maintain operational conditions for equipment. In order for the efficiency of the building to be improved or the use of the building to change, the building has to be partly or wholly demolished in favor of another structure that better serves the new purpose. All this is of course expensive in terms of energy and resource consumption.

IDEALS presents a radically different attitude toward building and building design. Rather than focusing on a static structure that is built for a specific purpose, an adapto-building is in certain senses a ***living*** structure that can adapt to daily changes for heating and cooling, transform shape seasonally to take advantage of environmental changes, and repurpose itself over time as user needs change. The PIs recognize that current building design philosophy that generally produces fixed structures of limited adaptability and largely single-use is unsustainable and that a new paradigm is necessary. IDEALS will develop the technologies necessary for adapto-structures, technologies that transcend the typical boundaries of mechanical, thermal, controls, structural engineering and architecture, and require an interdisciplinary, integrated approach.

- **Broader Impacts:**

The research purpose of IDEALS is to confront the grand challenge of adaptive and reconfigurable buildings. Outreach will take its principles to the broader sustainable building design community. This will be done in three ways.
(a) Developing transformative and interdisciplinary technology leading to energy savings over the entire life-cycle of the building. The total energy used for a building includes the embodied energy in its construction, energy consumption during use, embodied energy for renovations for both regular maintenance and repurposing of space, and demolition of the building at the end of its life-cycle. The sustainability of use measure will be developed specifically for this purpose.
(b) Direct dissemination of technology to industry in an interdisciplinary setting. To promote the implementation of the technology developed in this proposal and to seek feedback from leading professionals, a day-long interdisciplinary conference, which will include field-specific workshops led by each PI and interdisciplinary workshops aimed at integrated design practices, will be held at the University of Notre Dame. Prominent architecture and engineering firms will be invited to participate.
(c) Developing and teaching a new interdisciplinary design course at the senior-graduate level. To promote interdisciplinary collaboration, the PIs will develop and co-teach an interdisciplinary design course. Lectures will be taught by all PIs, with the aim of exposing undergraduates from different disciplines to adapto-design principles using the vocabulary of each field. Teams of students (with one from each area) will be tasked with a semester-long adapto-building design project, culminating in a final review by all PIs. Course materials will be freely available on an IDEALS website so that this course can easily be adopted at other institutions. Undergraduate and graduate students involved in this research will be mentored by field-specific PIs and in an interdisciplinary setting through bi-weekly group meetings.

- **How the project is better suited for INSPIRE than for a standard NSF proposal process:**

The truly interdisciplinary nature of this work requires a program like INSPIRE. The scope of IDEALS does not fit into any one discipline, and therefore does not belong in a single traditional program within NSF. Aspects of the work cover structural engineering, control systems, computational fluid dynamics, thermal engineering and sustainability. It includes topics that are normally within the purview of at least five different programs within the NSF.

- **Other comments:**

The concept of a reconfigurable space that is adaptive is not by itself a totally new idea. Studio spaces can be reconfigured by moving walls on sliders, and various architects and office suppliers have proposed, developed, and implemented similar concepts. However, these architectural solutions have confined themselves to reconfiguring walls only, without also exploring the opportunity for reconfigurable ceilings or orientations. Reconfigurable ceilings to provide vertical divisions of space have been suggested within the context of an open building plan, but have not been as widely adopted. While these concepts provide a context for IDEALS, they approach the problem only through the single discipline of architecture, with the goal of improving space usability. IDEALS, on the other hand, will take a multi-technology approach and will instead meld architecture with mechanical, thermal, controls, and structural engineering into an adapto-design methodology that both minimizes energy usage and maximizes sustainability. The integrated manner in which IDEALS will be carried out will be just as significant as the results.