Bringing the Built Environment to Life via Artificial Intelligence and Evolutionary Game theory and its impact on Resilience

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With the rise of the internet of things, we are getting closer to creating the Digital Twins of the built environment. Civil engineers are at their prime for modernizing the built environment that is increasingly more resilient against natural and anthropogenic hazards while conquering ambitious sustainable goals. The foundation for this ambitious vision is laid by combining the strengths of the following fields: artificial intelligence (AI) within computer science; game theory within economics and political, biological, and social sciences; system identification and damage detection within electrical and mechanical engineering; and smart structures and resilience from civil engineering.

What does it mean to bring the built environment to life?

The rationale to embrace a biomimetic built environment during extreme events has been articulated through the need to understand the tradeoffs among different disaster mitigation strategies that provide AI characteristics to the structure needed to combat the external forces from extreme events. The goal is to develop a new generation of smart/adaptive structures equipped with sensors and actuators in which sensors measure the response of the structure in real-time and actuators and damping devices apply the required forces to minimize the response of the structure. Smart structures modeled using AI are buildings and bridges equipped with the latest sensing and adaptive technology. Smart structures modeled for real-time adaptation has three major components: sensors to capture the environment surrounding the agent, a computer to process the information from the sensors and make decisions based on the information, and devices to perform the actions based on the computer's decisions. Smart dampers can redefine the loading path in a structure dynamically. Strategies for equipping buildings with smart dampers have been developed over the last decades through passive systems, semi-active systems, active systems, and hybrid systems(Javadinasab Hormozabad et al. 2021; Korkmaz 2011; Nishitani 2019; Spencer Jr and Nagarajaiah 2003; W Housner et al. 1997). Semi-active devices are particularly promising in addressing many challenges faced by this technology, offering the reliability of passive devices yet maintaining the versatility and adaptability of fully active systems(Gutierrez Soto and Adeli 2017a; Miah et al. 2017; Wang et al. 2009).

Notable examples of structures equipped with semi-active devices include the Bandaijima building shown in Fig. 1 which has 72 semi-active hydraulic dampers, HIDAX dampers by the *Kajima Corporation*. Since its construction, the data shows that the technology installed was effective in mitigating vibrations from the typhoon (increasing damping up to 4.2%) and earthquake loading (up to 3 times the sway during the 2004 and 2007 Niigata Chuetsu earthquake(Ikeda 2009)). Other adaptive technology includes active mass dampers or a combination of active and passive devices, which are installed in many tall signature structures around the world(Gutierrez Soto and Adeli 2013a; b, 2014).

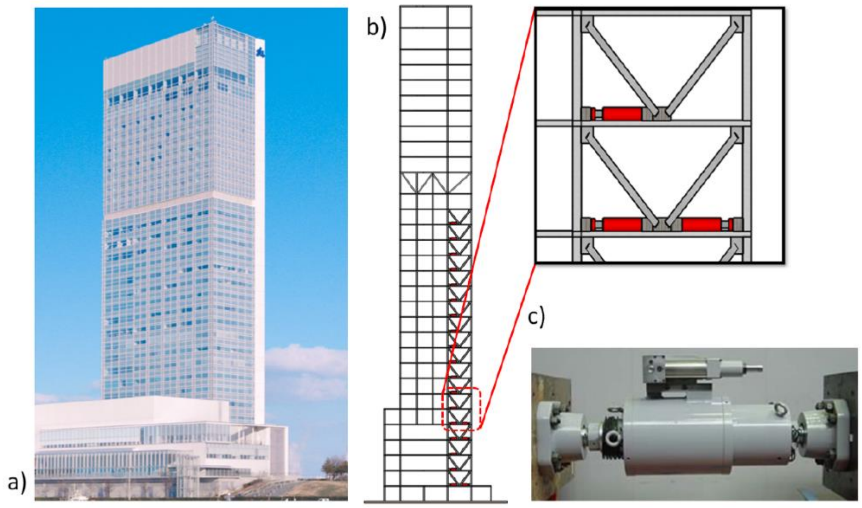

Figure 1 a) *Bandaijima building located in Japan equipped with 72 HIDAX-s semi-active hydraulic devices b) Elevation view with devices location c) close-up of the HIDAX device from the Kajima corporation*

AI is the simulation of human intelligence processes such as input information, learning, knowledge, making meaning, reasoning, conclusions, self-reflection, self-correction, and so on, by machines(Dadwal 2019). Developed in the AI community, an *agent* is an autonomous abstract or software entity that observes through sensors and acts upon an environment in an adaptive or intelligent manner(Lin et al. 2015; Mendoza et al. 2014; Pinto et al. 2014). In agent-based modeling, the agents are identified, and their behavior is defined. We can model what each agent does and model what the agents do together. Agent-based modeling is particularly appealing for large-scale problems because agents do not require that all the agents interact directly and have complete information about the system. Modeling for artificial agents is divided into simple reflex, goal-based, and learning agents(Bermúdez 2020). The complexity exists in modeling the interaction through the sensory systems and how each agent acts upon the environment. Modeling how agents simplify the complexity to predict, and act is a current challenge in agent-based modeling. Therefore, AI offers the bridge for smart structures to learn and adapt to their environment during their lifetime. Energy consumption is also at the core of a sustainable design(Katsigarakis et al. 2016) Recent advances in data-driven control methods include the power available (i.e., an emergency generator) at the core parameter for dynamic resource allocation(Gutierrez Soto and Adeli 2017b; Obando et al. 2013) Therefore, semi-active devices controlled by data-driven methods would enable the adoption of such innovative technology. One fascinating approach is using *evolutionary game theory* as the inspiration for the control methodology.

How can we use game theory in civil engineering applications?

While the concept of game theory has traditionally been studied in political(Robinson and Ullman 2016), economics, and social science(Straffin Jr 1993), the mathematical modeling of cooperation and competition is useful in modeling the brain of a machine(Vincent and Brown 2005). Specifically, the brain of the control agent is set up with strategies, which enable the computer to exhibit rational behavior. Game theory has been used in conjunction with AI for autonomous drones and robotic organizational tasks(Spica et al. 2020). Recently, the evolutionary game theory of replicator dynamics started immersing in engineering(Barreiro-Gomez et al. 2015). Replicator dynamics models how natural selection affects the population according to their habitat in an environment based on a measured fitness function or pay-off(Nowak 2006). The number of individuals in each habitat varies because of the interaction and comparison with the average fitness of the total population. Population dynamics is a technique used for the distribution of water in a distributed network (Ramirez-Llanos and Quijano 2010), optimal resource allocation in an electrical power grid distribution(Pantoja and Quijano 2011), and for controlling temperature for improving the energy efficiency in buildings(Obando et al. 2013). Recently, the DREAM structures lab developed a novel data-driven methodology that integrated artificial intelligence, evolutionary game theory, and decentralized control(Gutierrez Soto and Adeli 2017b). We studied the proposed method to reduce vibrations of low- and high-rise buildings(Florez et al. 2021; Gutierrez Soto and Adeli 2017c), smart base-isolated structures(Gutierrez Soto and Adeli 2018), and highway bridge structures(Gutierrez Soto and Adeli 2019; Javadinasab Hormozabad and Gutierrez Soto 2021a). Another application of game theory and other soft computing methods is a design optimization technique. Neural dynamic modeling has already been effective in providing cost-benefit solutions for structural design optimization of diagrid building structures(Palacio-Betancur and Gutierrez Soto 2022) and controlled rocking steel braced frames (Javadinasab Hormozabad and Gutierrez Soto 2021b) as well as obtaining optimal control parameters for advanced vibration mitigation .

The performance of the proposed control approaches is done using real-time hybrid simulation (RTHS) shown in Fig. 2. RTHS is a cyber-physical testing approach that combines experimental and analytical substructure configuration(Gálmez and Fermandois 2022; Palacio-Betancur and Gutierrez Soto 2019). It allows studying the performance of rate-dependent devices while modeling complex tall structures numerically. Many researchers have studied the behavior of magnetorheological dampers using this technology (Al-Subaihawi et al. 2020; Asai et al. 2015; Bonnet et al. 2008; Chen and Ricles 2010; Christenson et al. 2008; Dyke et al. 1996; Li et al. 2017). Although the majority of RTHS was focused on seismic applications, recent vibration mitigation discoveries using RTHS have investigated other hazards such as wind (Al-Subaihawi et al. 2020). Future research could investigate the harvesting of energy from these mechanical vibrations adopting similar concepts from wave energy conversion (Gallutia et al. 2022).

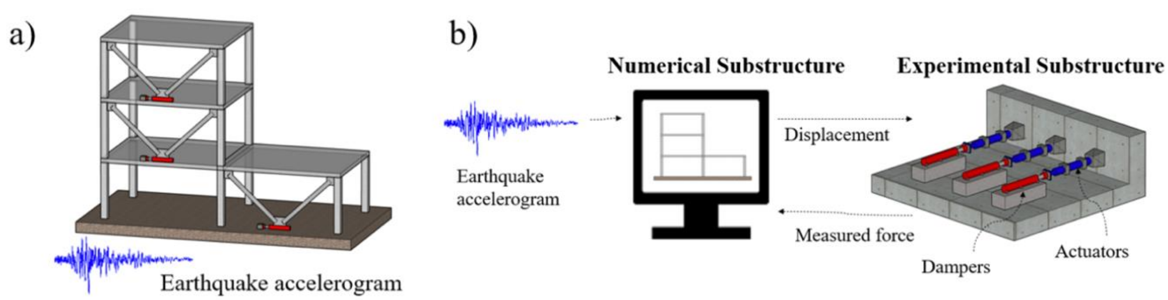

Figure 2 a) Test specimen of smart structure subjected to earthquake loading b) Setup for Real-Time Hybrid Simulation with the building as numerical substructure and damping devices as experimental substructure.

How can we use technology to identify complex structures' behavior and detect damage in real-time?

Understanding the behavior of complex structures has recently been rapid due to the advances in sensors and software technology(Singh et al. 2019). Moreover, the accuracy of structural assessments can be improved by analyzing recorded structural response data for optimally scheduling maintenance and repair activities. By carefully crafting sensor networks and signal processing algorithms, we can link sensor data to condition assessment(Lughofer and Sayed-

Mouchaweh 2019). Sensory information and data processing are useful to fundamentally understand the structural dynamics of complex building structures. Acceleration measurements captured through accelerometers provide global information about the structure such as mode shape changes, frequency variations, and dynamic flexibility(Caspeele et al. 2018; Frangopol and Messervey 2009). Abdelrazaq (2011) used system identification techniques to validate the dynamics of the Burj Khalifa, the tallest building in the world (Guo et al. 2015; Kijewski-Correa et al. 2013; Spence and Kareem 2014). Seismic responses obtained from smart systems installed in constructed structures have been used to verify seismic design(Fujino et al. 2019). By inverse method, for example, the properties of the structure are identified and changed during or after extreme events. Only when structures are impacted by actual natural hazards, can we test the appropriateness or limitations of design assumptions during loading conditions and observe the possibility of new structural behaviors that were not considered in the design stage.(Fujino et al. 2019) Design assumptions and parameters can be validated with the potential benefit of improving design specifications and guidelines for future structures. Traditionally, successful ultra-high precision control design and implementation depended on the accuracy of the system model. However, system identification techniques now provide tools for this purpose(Ljung 1999). The self-diagnosis and prognosis of the structure are done using vibration-based system identification, which uses the vibrations propagated in the building to identify the changes in the properties of the structure. Among the most important damage detection issues with any technique is its reliability. Errors at the detection level have hindered its inclusion in automotive industries. System identification techniques based on AI have been shown to provide good accuracy, but they are computationally expensive and require training, validation, and testing datasets(Salehi and Burgueño 2018).

Most current research in system identification focuses on the implementation and validation of damage detection algorithms, sensors, and sensor networks, while robust software platforms designed to facilitate collaborative efforts that support data usage, data archiving, and automated processing of monitoring tasks have received less attention(Smarsly et al. 2012). A critical challenge in the safety and serviceability of large real-life structures is automated detection of damage out of the huge amount of data collected on a daily, weekly, and monthly basis through sensing information(Amezquita-Sanchez et al. 2017). Vibration data collected from large structures are often very noisy. The methodologies for online SHM should handle noisy data effectively, and be accurate, scalable, portable, and efficient computationally(Javadinasab Hormozabad and Gutierrez Soto 2021c). Avci et al. (2021) reported that unsupervised deep learning vibration-based damage detection shows promise in automation. Between natural hazards, a self-diagnosis is performed and could activate the self-healing protocol for the sections impacted and prepare a prognosis(Napolitano et al. 2021). This system will enable smart structures will have an interface to communicate with building owners, users, and other entities to enhance smart cities' response. The future built environment should be able to interact with humans, communicate with other intelligent systems interacting in the environment (e.g., self-driving vehicles, water distribution networks, and so on), and achieve resilient and sustainable goals through real-time adaptation to multiple hazards.

How does smart structure relate to community resilience?

Bruneau et al. (2003) define four resilience attributes: robustness, redundancy, resourcefulness, and rapidity. The community resilience frameworks incorporating all four attributes of resilience allow a holistic resilience quantification approach to aiding decision-makers before, during, and after emergency situations(Kammouh et al. 2019). Cimellaro et al. (2016) incorporate the four forms of resilience: technical (i.e., capability to function and perform), organization (i.e., organization's aptitude to manage the system), social (i.e., society's effort in dealing with the services' deficiencies), and economical (i.e., the competence to decrease both indirect and direct economic costs) measures. *Robustness* is seen technically as the degree of avoidance of damage, organizationally as the ability to continue community essential functions, socially as casualty avoidance and disorder in the community, and economically as avoidance of direct and indirect losses(Bruneau et al. 2003). Kammouh et al. (2018) proposed resilience frameworks to aid decision-makers within the community to act early and improve the areas of the community that require more resilience efforts before a disastrous event occurs. Locations that have been impacted by recent earthquakes, hurricanes, and tsunamis form prime opportunities to learn how the hazard impacted the built environment. Community resilience frameworks enable researchers to quantify the impact of the mitigating measures (individual scale) at the community level. Melendez et al. (2022) provide more information about computational methods for community resilience. The life-cycle analysis of smart technology systems as researched in(El-Khoury et al. 2018; Micheli et al. 2020) provides insight into its immediate and long-term benefits. Future research is required to study resilience frameworks to quantify the benefits of using smart devices as an advanced mitigating solution, especially for multiple hazard events(Bruneau et al. 2017).

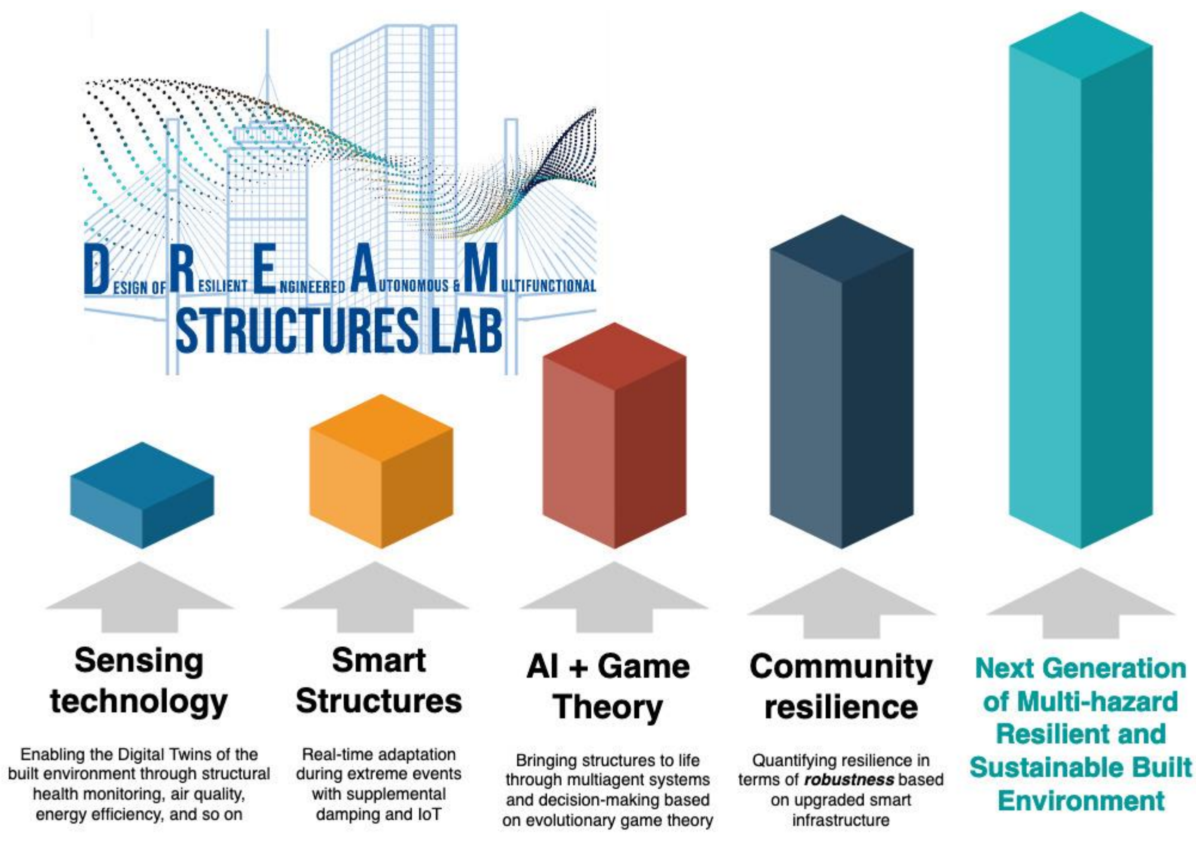

Figure 3 Discoveries Bringing the Built Environment to Life in the DREAM Structures Lab

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