ABSTRACT
The paper introduces a novel approach to programmable material for optimal energy building skins. The use of shape memory alloy wire Flexinol®, trade name for Nitinol, exploits an atomic-level phase change that occurs at a length-scale of just over a tenth of a nanometer. The resulting behavior of the wire produces a scalar shift on an order of many magnitudes. In the simplest terms, the wire exhibits a direct translation of heat into human-scale work. By engineering the specific heat or energy required for martensite phase change within the team’s bespoke Flexinol® actuator assembly, we will show that a man-made material system can be programmed to respond to its environment without the use of an electrified logic system. This research fundamentally shifts kinetic shading technologies away from electrified sensors and actuators to a smart material capable of sensing its environment, measuring a gradient, and actuating a response through a uniquely programmed chemical composition. This paper will present a first of its kind, full-scale production of a dynamic passive shading screen from design development through construction with a discussion of results following the screen’s exhibition in the 2013 U.S. Department of Energy Solar Decathlon.
INTRODUCTION

In 2011, The Catholic University of America, The George Washington University, and American University, joined together to form Team Capitol, DC to compete in the 2013 U.S. Department of Energy Solar Decathlon competition in Irvine, CA. The biannual competition calls for twenty collegiate teams from around the world to design, build, and operate solar-powered, cost and energy efficient homes. Team Capitol DC’s entry, Harvest Home, is an innovative residential prototype that harvests energy flows to power the home while also maintaining comfort for its final user, a wounded American veteran. A key feature of the home’s design is the Harvest Shade Screens, which, to the best of these authors’ knowledge, is the first full-scale application of a commercially viable Nitinol-based passive shading screen.

The Harvest Shade Screens approach a centuries-old building system, the shutter screen, through novel material technologies, optimal energy approaches, and industrialized fabrication processes. The screen design is the culmination of a multi-year research agenda into environmental, user-oriented building skins by the Emerging Technologies Graduate Concentration at the Catholic University of America’s School of Architecture and Planning (CUArch) in collaboration with Dynalloy Inc. (Dynalloy), an industry leader in the manufacturing and engineering of the shape memory alloy (SMA), Flexinol® wire, a nickel-titanium (NiTi) alloy, or Nitinol (Team Capitol DC, 2013).

Located on a large section of operable glazing, composing twenty per cent of the residential prototype’s southern façade, the horizontal louvered system serves a multifaceted intent: insulate the building from direct solar radiation, control the passage of reflected light, allow cross-ventilation, and maintain privacy. Pragmatically, the screens function based on historically established passive shading strategies and irradiance analysis conducted using the Rhinoceros 3D modeling environment plug-in, DIVA-For-Rhino. However, the Harvest Shade Screens imbued a more novel, techno-environmental potential. Through the design and development of a Flexinol® wire actuator, the Harvest Shade Screens ‘harvest’ the latent energy of the sun to passively shade the house’s southern façade by closing the horizontal louvers through a rotational movement that requires no additional energy sources. This phototrophic movement introduces an entirely new paradigm to the built environment, allowing for a ‘living’, ‘breathing’ architecture. (Team Capitol DC, 2013)

Since the late 1990s and the critical work of MIT’s House (Intille 2002) and University of Colorado’s Neural network House (Mozer 1998), along with a large commercial push for “smart devices” as seen by the writings of William Mitchell (Mitchell 1996), and corporations such as Trane, Seimens, and the now popular Nest, building automation for the purpose of energy conservation and climate control have tended toward increased “intelligence” through adaptation of algorithm-based machine learning, integrated microprocessing, and networked sensory devices with existing heat, ventilation and cooling (HVAC) systems. However, as Michelle Addington notes, “Indeed, the issues that arise here remind us that the twentieth century interior environment has been determined by the available technology, and not that the phenomenological interactions determined the technology” (Addington 1997). For this reason, we propose research into material-based logic systems that can be chemically and physically programmed to compute a Boolean, or gate logic, in direct response to a thermo-dynamic gradient for the purpose of optimizing energy exchange through the building envelope.

FRAMEWORK, A TECHNICAL REVIEW OF SHAPE MEMORY ALLOY, NITINOL: NITINOL IN THE BUILT ENVIRONMENT

Shape memory alloys (SMA) are not new in contemporary consumerism. Research into SMAs began in the 1930s leading to the discovery of the nickel-titanium alloy, Nitinol, in 1961. The nickel-titanium chemical make up of Nitinol allows the material to contract when heated. Commonly manufactured as wire extrusions, the typical contraction will range between two to five per cent of the overall length of wire. Nitinol alloys are made of a composition of roughly 55 to 56 per cent nickel and 44 to 45 per cent titanium. Changes to this chemical composition allow for significant impact on the transition temperature to achieve modification of the SMA (http://www.dynalloy.com/AboutFlexinol.php).

As stated, contemporary consumers are quite familiar with products that use SMA technology, though they may not be aware of the alloy. The properties of SMAs have been implemented on multiple scales within the medical industries ranging from orthodontic guide wires to cardiovascular application of self-expanding NiTi stents. Electronic applications for shape memory Nitinol include microcircuit breakers, PC mount relays, temperature controls and electronic locks, to name a few. Research into Nitinol-actuated responsive and interactive systems have become popular within academic design discourse. Projects designed by the likes of Rob Ley and Joshua Stein, Phillip Beesley, The Living, Decker Yeadon, and Andrew Payne, have provided promising examples of Nitinol-actuated architectures. However, the majority of systems developed within academia have struggled to establish a full-scale building application because of the alloy’s narrow thermal hysteresis at applicable temperature ranges, high fatigue life at high
stress, high transformation strain and forming of wire connections (Browne et al. 2011). One system of note that is commercially available for environmental control systems is the Titus linear diffuser that change the position of heated and cooled air distribution, high and low respectively, through the passive actuation of the Nitinol wire by the heated forced air. This energy potential, the capacity for linear actuation through the physical augmentation of the Nitinol wire by relatively low temperature gradients, provides a primary precedent for a novel, optimal energy, programmable kinetic architecture.

MARTENSITIC TRANSFORMATION
The actuation, or contraction, of the Nitinol wire is a solid-state phase transformation based on atomic-level characteristic of the nickel-titanium alloy (martensitic transformation). The atomic-level changes are understood through three phase change periods, martensite, austenite, and hysteresis. Understanding of these phases allows for greater understanding of the application of the Nitinol wire in the Harvest Shade Screen.

At low temperatures the Nitinol wire is in a martensite crystal structure (Figure 2). This more complex structure represents the normative or relaxed state of the wire. When heat is applied, the wire exhibits a cubic crystal structure, or austenite structure. The atomic-level change from martensite to austenite results in a 2 to 5 per cent stress or contraction of the wire. The resulting stress also exhibits a large mechanical force upwards of 25,000 PSI. During the austenite phase, the crystal structure of the wire is deformed without breaking atomic bonds, allowing the reversal of the solid-phase change when cooled, and the alloy’s ‘shape memory’ (www.dynalloy.com/pdfs/TCF1140.pdf). The NiTi alloy also exhibits a large hysteresis, the change in temperature between full austenite and full martensite, typically in the order of 25 to 50°C (Figure 3). The large hysteresis phase means that a temperature change to the wire within a predictable range will not modify the physical properties of the wire; therefore the wire exhibits a lag, or delayed change from full contraction to relaxation.

DESIGN PARAMETERS
In the Spring of 2011, CUArch’s Emerging Technologies Concentration established a research collaboration with Dynalloy Inc., an industry leader in the manufacture and engineering of nitinol, trade named Flexinol® wire. Through this collaboration, a series of prototypes were developed exploring the capacity of a Flexinol® actuated shading system. Prototypes evaluated the physical properties of Flexinol® wire to actuate mechanical systems, the programming of embedded microprocessors for sensory-driven actuation of electrically induced contraction, and computer numerically controlled (CNC) fabrication methods. Through these prototypes, three design criteria were established including:

1. passive transformation of Flexinol® wire through both radiant and ambient heat
2. reduced design complexity through inline actuation and limited number of Flexinol® assemblies
3. reduced friction at axial rotation points with a ten grams maximum pull force required per louver.

The chemical makeup of Flexinol® alloys allows engineers to program the specific temperature and stress at which the wire undergoes an austenite transformation by changing the proportion of nickel to titanium within the alloy. While phase change
temperatures range from 200°C to near cryogenic temperatures, chemically programming of Flexinol® wire requires extensive engineering and analysis that fell beyond the scope of this project (http://www.dynalloy.com/AboutFlexinol.php). Fortunately, based on precedent research conducted before collaboration with Dynalloy, the established austenite temperature range, 15 to 30°C, fell within an existing wire specification manufactured by Dynalloy. The specified wire had an allowable pull force of 2500 grams during the cool, martensite phase, and a 2900 gram pull force during the heated austenite phase, resulting in a total actuation force of 400 grams.

In order to ensure the specified wire would produce a phase change in response to ambient temperature and direct radiant heat gain, an austenite temperature range was established by evaluating annual temperature data for Irvine, CA during the competition period, October 3rd to 14th (Figure 5), (Figure 6). Evaluating annual weather data trends showed that for the month of October, austenite phase change could be produced above 25°C, with a large enough temperature change, 10°C, to return the wire to a relaxed martensite phase change below 15°C. Furthermore, irradiance trends ensured that additional radiant heat would provide necessary added energy to ensure a minimum temperature of 25°C would be reached during peak heat gain periods.

DESIGN

Pragmatically, the Harvest Shade Screens’ design is based on four primary parameters: insulate the building from direct solar radiation, control the passage of reflected light, allow cross ventilation, and maintain privacy. Within the context of the Harvest Home residential prototype, the shade screen design operates two distinct passive solar shading paradigms.
The physical design of the Harvest Shade Screen is based on historically established passive shading strategies and energy and day-lighting analysis through DIVA-for-Rhino. In order to establish a depth and spacing of the horizontal louvers, two key factors were calculated: site specific solar altitude during optimal periods of shading, and the window azimuth for the louvers’ orientation. The team used an industry standard equation to compute the depth-to-height ratio (Brown 2001).

\[ H = \frac{D \cdot \tan(X)}{\cos(S-W)} \]

Where \( H \) is the vertical spacing between louvers, \( D \) is the depth of each louver, \( X \) is the solar elevation, \( S \) is the solar azimuth and \( W \) is the window azimuth. The solar altitude, 50 degrees, was established by using the fall equinox at 15:00, which closely corresponded with the start of the October 1st Solar Decathlon competition period. The window azimuth for the southern exposed louver was calculated as zero since the louvers are exposed parallel to the southern azimuth. These factors provided a 1:1.2 depth to spacing ratio. Therefore, the louver spacing was established at a near 1:1 depth-to-height ratio. Further analysis through DIVA-for-Rhino confirmed that the screen’s eighty percent transparency (when viewed in direct elevation) allowed for an optimal solar illumination and the 1:1 ratio provided an optimal insulation from direct radiant heat gain.

Further esthetic modifications were applied to the screen system to provide a richer texture, a more inviting user experience, and the manipulation of reflected light when in the open position. First, the extruded louver’s shape was tapered into a truncated isosceles triangle, providing a contiguous rhythm across the screen façade. To ensure the nonuniform shape provided adequate shading, louver spacing was proportionally reduced based on the average of the profile widths. Second, a 25-degree structural bend was placed along the louver cross section. Again, the bend increases visual texture, but also directs reflected light onto the ceiling and bottom face of adjacent louvers throughout the day to produce an illuminated wall section and reduce incidences of direct solar glare.

The use of a Flexinol® actuated passive shading screen introduces novel approaches to programmable material for optimal energy building skins. While the screen’s static passive system is designed to
ensure adequate shading without the closure of the louvered façade during the October competition period, the capacity for increased insulation by means of automated closure at peak radiation periods for the continuum of the year ensures optimal annual thermal protection.

Through extensive collaboration with engineers at Dynalloy, a fully integrated Flexinol® actuator assembly was developed. As stated earlier, the 15 to 30°C temperature range for Irvine, CA, fell within an existing specification for a wire manufactured by Dynalloy. The specified wire allowed a 2500 gram force during the cool, martensite phase, and a 2900 gram force during the heated austenite phase, resulting in a total actuation force of 400 grams. In order to produce a rotational movement with limited friction, an inline pulley system was developed that allowed a single Flexinol® wire to actuate the thirty-two horizontally arrayed louvers with a maximum resistance force of 10 grams per louver. A single spring runs the length of the assembly, this spring ensures the Flexinol® wire remains under the prescribed 2500 gram load during the martensite phase, allowing for proper actuation under specified heat. When heated, the contraction of the wire rotates a large idler pulley at the top of the assembly that uniformly transfers rotational force via Kevlar strings to each pulley of the assembly, rotating the louvers. When the wire cools, the 2500 gram force of the spring acts to restore the wire, and louvers to the original open state.

Additionally, the specified wire’s transformation temperature range, between 15°C to 30°C, affords the system an added capacity to ‘tune’ the actuation point to a desired temperature. By placing a threaded connection at the base of the Flexinol® actuator assembly, additional stress can be placed on the wire. Added stress lowers the temperature of phase change by requiring more energy, or a larger heat gradient, to transition the molecular structure from martensite to austenite phase. The added stress...
allows the end users to program the exact actuation point to their desired temperature level within a 5°C range. Furthermore, the large hysteresis period both slows the rotational closure of the louver and ensures that minute temperature fluctuations do not result in continuous opening and closing cycles.

A key design parameter was to fabricate the Flexinol® actuator assembly within a near-universally accepted commercial building component. The final assembly is designed to fit within a standard aluminum mullion system. Fabrication within these specifications required tightly controlled parameters to both ensure dimensional accuracy and precise alignment of components in order to reduce potential energy transfer loss through friction of the in-line pulley assembly.

CNC fabrication equipment was used extensively in the screens production. In-house fabrication facilities, specifically a Techno 3-Axis-CNC mill, provided both a controlled and cost efficient means of cutting each of the 250 sixteen gauge, powder-coated aluminum louvers in the final assembly. CNC milling also ensured accurate placement of holes along each aluminum channel used for the screen frame and assembly housing. Accurate spacing ensured that each of the thirty-two aluminum rods in the pulley assembly would not produce rotational friction and binding.

Finally, the novel tectonics of the pulley assembly required custom manufacturing of parts through acrylonitrile butadiene styrene (ABS) fused deposition modeling per the team’s in-house printing facilities. Commercially available pulleys were researched, however, cost and lead times proved to be prohibitive for the fast-tracked construction schedule. Furthermore, engineering and fabrication of a more complex, helical channel about the pulley’s drum ensured proper tensioning of the Kevlar pulley-to-pulley connection string.

RESULTS
The Harvest Shade Screens were installed and exhibited in Irvine, CA for a three-week period between September 22nd and October 12th. Weather data for the venue was collected by the Department of Energy at fifteen-minute intervals for the entirety of the competition period. Photo imaging was used between 9:00 and 17:00 on September 29th at thirty-second intervals to measure the rotational movement of louvers. The average ambient temperature during this period was 25°C with a peak temperature of 28°C. The average solar irradiance was 440 W/m² with a peak irradiance of 731 W/m².
During morning monitoring the shade screen panels were exposed to solar irradiance at 9:15. When first exposed, the screens had a positive, 105 degree rotation in the open position. The ambient temperature was 23°C, and average radiant heat gain was 266 W/m². Between 9:30 and 10:00 the louvers exhibited continuous closing rotation for thirty minutes, rotating from the initial 105 degree position to 25 degrees at a total transition rate of 2.5 degrees per minute. Full closure from 25 degrees to 0 degrees took an additional 30 minutes at a transition rate of 1.0 degree per minute.

Sunset monitoring of the shade screens showed an opening rotation from 0 to 15 degrees between 19:15 and 19:30 at a transition rate of 1 degrees per minute and full opening from 15 to 90 degrees from 19:30 to 19:45 at a transition rate of 5 degrees per minute. During this period the average temperature was 21.5°C and average irradiance was 0.5 W/m².

DISCUSSION
The result of the exhibition of the Harvest Shaded Screens show, to these authors’ knowledge, the first full-scale commercially viable application of a programmable Nitinol-based system for passive shading and irradiative insulation. The data collected in the above section provides key feedback for proof-of-concept and further development. The specific wire used in the Flexinol® actuator assembly has a 15°C to 30°C phase change temperature range. During the wire assembly’s fabrication, the Flexinol® was stressed at 20°C to program the wire to undergo phase change at the specified temperature of 20°C (martensite) and 30°C (austenite). As exhibited by the morning solar exposure, the screens transitioned at an ambient temperature of 25°C, while this temperature is below the expected 30°C temperature for phase change, it does show an
During the morning austenite phase, as exhibited by the last 25 degrees of rotation occurring at 0.4 degree/min, and during the evening martensite phase change with the first 15 degrees occurring at 1 degree/min.

Hysteresis also expresses a key benefit of Nitinol. The large temperature gradient from martensite to austenite phase change, approximately 10°C, provides a chemical ‘buffer’ or signal smoothing response. During the observation, solar irradiance dropped from the daily peak of 747 W/m² to 105 W/m² for sixty minutes, causing a 1.5°C drop in ambient temperature. While the exact temperature within the actuator assembly was not recorded, the records show that the screens did not open. This buffered response shows that the consistency of the screen mechanism produces a response across a larger, near-diurnal cycle, instead of a 1:1 response.

CONCLUSION

The Harvest Shade screens introduce a novel approach programmable for material for optimal energy building skins. The use of Flexinol® wire exploits an atomic-level phase change that occurs at a length-scale of just over a tenth of a nanometer. The resulting behavior of the wire produces a scalar shift on an order of many magnitudes. In the simplest terms, the wire exhibits a direct translation of heat into human-scale work. By engineering the specific heat or energy required for martensite phase change within the Flexinol® actuator assembly, we have shown that a material system can be programmed to respond to its environment without the use of an external power or logic system.

This research into environmentally controlled kinetic shading devices introduces new horizons for intelligent building skins. In the case of the residential prototype, the building typology and end-user provide a unique opportunity to condition space. In the context of skin loaded residential building, energy consumption for heating and cooling loads represent thirty and twelve percent of total energy loads, respectively (Smil 2008). Residential building also represents an occupancy type that is typically uninhabited during peak radiant gains. The capacity for a shade screen that can actively respond directly to solar radiant heat gains by closing and opening in direct response to long-wave radiation and ambient temperate without either a human actuated closure or an energy consuming electronic sensor and motion control system radically shifts the perception of a ‘smart building,’ or ‘building automation system’.

Effective response to solar radiation on the assembly, the average 440 W/m² provided enough long-wave radiation and energy absorption by the aluminum assembly housing to produce a phase change in the wire at or above 30°C. Furthermore, the initial fifteen-minute lag at which time no rotation was recorded further supports the need for solar radiation to heat the aluminum channel to a temperature above 30°C.

At night the opening of the screens responded near-perfectly to the sunset in Irvine, CA. The average temperature of 21.5°C with a peak low of 20°C provided an ambient temperature low enough to produce a phase change and the timing of closure with a near 0 radiant gain.

The data provided also highlights a key characteristic of Nitinol: hysteresis. As seen in (Figure 3), the energy required for phase change during initial and end phase requires more energy for a smaller displacement. This phenomenon is exhibited both during the morning austenite phase, as exhibited by the last 25 degrees of rotation occurring at 0.4 degree/min, and during the evening martensite phase change with the first 15 degrees occurring at 1 degree/min.
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