

Composite Systems for Lightweight Architectures

Case studies in large-scale CFRP winding

Andrew Wit

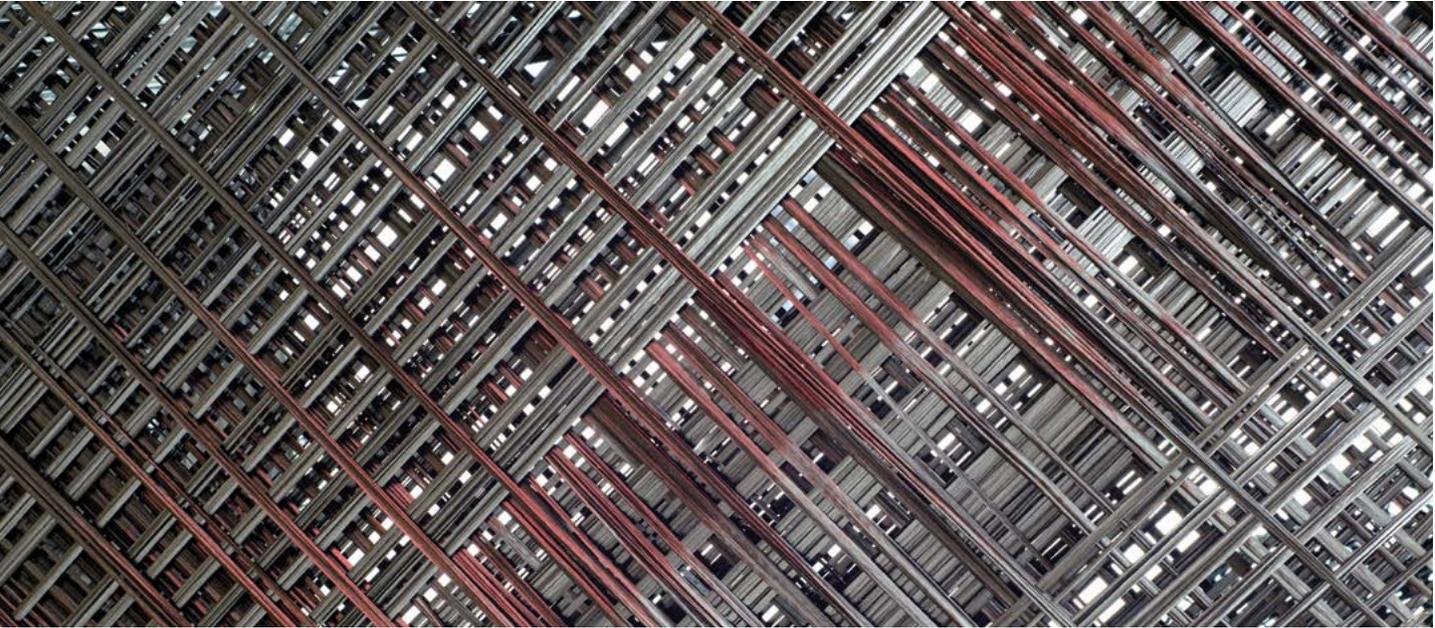
Rashida Ng

Cheng Zhang

Temple University

Simon Kim

University of Pennsylvania



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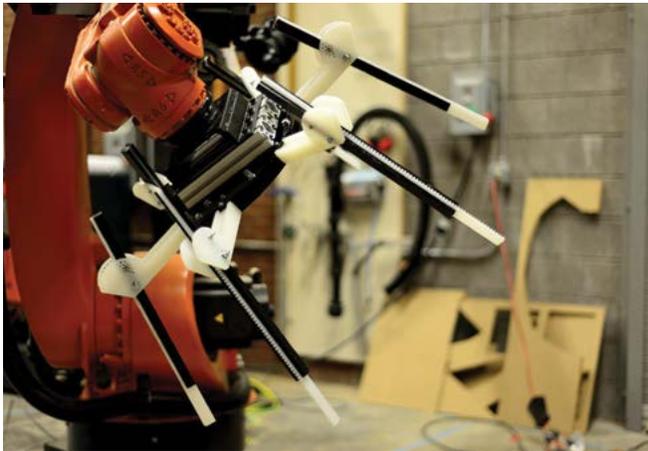
ABSTRACT

The introduction of lightweight Carbon Fiber Reinforced Polymer (CFRP) based systems into the discipline of architecture and design has created new opportunities for form, fabrication methodologies and material efficiencies that were previously difficult if not impossible to achieve through the utilization of traditional standardized building materials. No longer constrained by predefined material shapes, nominal dimensions, and conventional construction techniques, individual building components or entire structures can now be fabricated from a single continuous material through a means that best accomplishes the desired formal and structural objectives while creating minimal amounts of construction waste and disposable formwork. This paper investigates the design, fabrication and structural potentials of wound, pre-impregnated CFRP composites in architectural-scale applications through the lens of numeric and craft based composite winding implemented in two unique research projects (rolyPOLY + Cloud Magnet). Fitting into the larger research agenda for the CFRP-based robotic housing prototype currently underway in the “One Day House” initiative, these two projects also function as a proof of concept for CFRP monocoque and gridshell based structural systems. Through a rigorous investigation of these case studies, this paper strives to answer several questions about the integration of pre-impregnated CFRP in future full-scale interventions: What form-finding methodologies lend themselves to working with CFRP? What are the advantages and disadvantages of working with pre-impregnated CFRP tow in large-scale applications? What are efficient methods for the placement of CFRP fiber on-site? As well as how scalable is CFRP?

- 1 CFRP winding detail from the rolyPOLY prototype.
- 2 roboWINDER CFRP winding prototype.
- 3 rolyPOLY on display at the Tyler School of Art.

INTRODUCTION

As global populations continue to rise and environmental conditions become increasingly unpredictable, material and resource availability will become an ever greater problem affecting the discipline of architecture, especially following times of disaster. With the vast amounts of resources required to create current building typologies, the formulation of a more robust, intelligent, adaptable, yet affordable housing system will become an ever more significant issue. Existing housing typologies in the U.S. find themselves lagging behind other industries such as aerospace and automotive, lacking advanced lightweight materials, novel fabrication methodologies and adaptability, as well as embedded intelligent systems allowing for more efficient building processes, minimization of waste and a reduction of life-cycle energy consumption.



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In 2013, the “One Day House” initiative commenced, which is focused around the creation of a new typology of housing. Based around a wound composite structural system, adaptable robotic skin and intelligent living systems, the project called into question our understanding of the dwelling and its role in society. To realize the project, a series of short-term prototypical projects were initiated, each solving a single aspect associated with this newly proposed building typology. Initial research focused around material processes, adaptive systems and the utilization of industrial robotics for CFRP placement (Figure 2).

This paper investigates two recent projects (rolyPOLY + Cloud Magnet) to understand how novel material and fabrication methodologies, along with formal adaptability and environmental responsiveness, could be integrated into the larger research question centered around the creation of the “One Day House”.

CFRP

The introduction of CFRP into the discipline of architecture

has opened up new opportunities in the design, engineering and fabrication of large-scale, lightweight structures as found in recent research completed at the University of Stuttgart (Dörstelmann, et al 2015, Reichert, et al 2014). CFRP’s ability to effortlessly vary density, patterning and overall shape allows for the creation of forms, efficiencies and visual/tactile qualities that were previously impossible to achieve through traditional materials and processes. Additionally, the introduction of robotic coreless FRP winding has removed previous constraints requiring time- and money-intensive formwork that limit design freedom while creating vast amounts of waste (La Magna, et al 2016).

Building upon CFRP’s robust properties, in addition to previously completed projects in robotic coreless winding (Wit, et al 2016), both of the discussed projects utilized CFRP for their overall design and fabrication. A pre-impregnated resin system was chosen for consistency, stability, low-temperature curing, structural attributes and minimal toxicity. Two CFRP strand counts with identical resin systems ($\pm 27.51\%$ resin content) were utilized. rolyPOLY was wound from a 12K strand CFRP tow while a 24k strand tow was chosen for Cloud Magnet. The resins required a firing duration of 4 hours at 260°F for curing.

CASE STUDY 1: ROLYPOLY

Following the completion of several small-scale projects focused around robotically wound CFRP, rolyPOLY was initiated as the first large-scale intervention. Designed as a traveling exhibition (Figure 3), the artifact functions as a reconfigurable shelter for a single occupant while remaining structurally stable in all orientations. Through the operation of assisted tumbling, unique spaces, opacities and textures are created.



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Based on a sphenoid hendecahedron with two open faces, each 7' x 4.5' x 4.5' module easily aggregates with adjacent modules creating larger, more complex, self-supporting structures. Wound

from a single strand, each module contains over 100,000 linear feet of CFRP tow with a minimal self-weight of ± 20 lbs. Additionally, the design and implementation of variable methods for fiber winding created varying skin thicknesses ranging between 1/16" - 1/4" while simultaneously allowing unique winding patterns to emerge. Initially requiring 24 hours of winding, subsequent projects have substantially reduced winding times making the process more feasible for large-scale architectural applications.

Methodologies

Rather than allowing aesthetics to dictate the artifact's design, material processes were utilized for formal definition. The processes and structural characteristics tested throughout the design defined the overall aesthetics and were as follows: 1. Part minimization through self-supporting monocoque shells; 2. Material/structural optimization through tensile form-finding; 3. Waste elimination through coreless CFRP winding; 4. Seamless fabrication of unique elements through reconfigurable/reusable framework; 5. Unique structural, visual and tactile effects through variable winding patterns.

To facilitate a robust form able to handle stresses from inhabitation and tumbling, a monocoque structure was chosen. In addition to strength, the single structural unit minimized complexity during fabrication as no assembly was required; allowed for continuous winding of the structure as a whole; enabled consistent structural properties by firing the entire artifact at once; and showed promise for easy scalability in our move towards an architectural scale.

For the fabrication of a successfully wound shell, it was necessary for all surfaces to maintain double curvature, creating maximum tensioned fibrous overlap. As the base form contained no double curvature, tensile cable/membrane simulation was utilized through the MPanel and Kangaroo interfaces, converting the form's linear edges into catenary cables stressed under predefined loads. Simultaneously, doubly-curved tensile membranes were created between the newly redefined edges. Lastly, the new membranes were deflated by a factor of 10%, simulating surface deformation encountered during fiber winding.

To facilitate CFRP tow winding, a reconfigurable steel frame was created. The frame consisted of 8 unique elements of 3-4 curved, welded edges, each bolted together on-site with conduit hangers forming the 10 doubly curved surfaces of the artifact. Upon assembly of the steel frame, plywood CFRP grippers were laser cut and attached to the frame through a similar system (Figure 4).



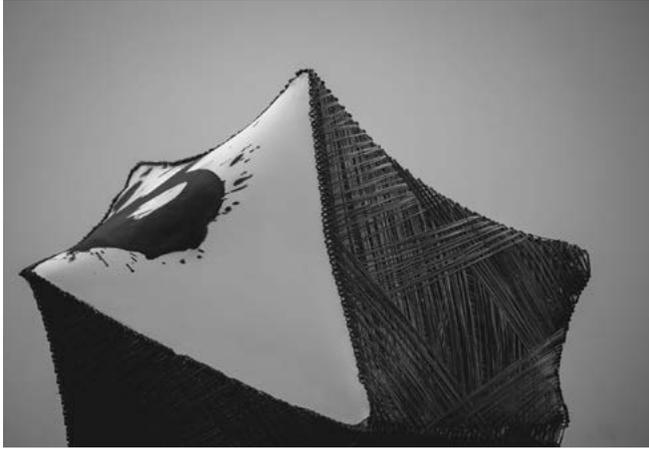
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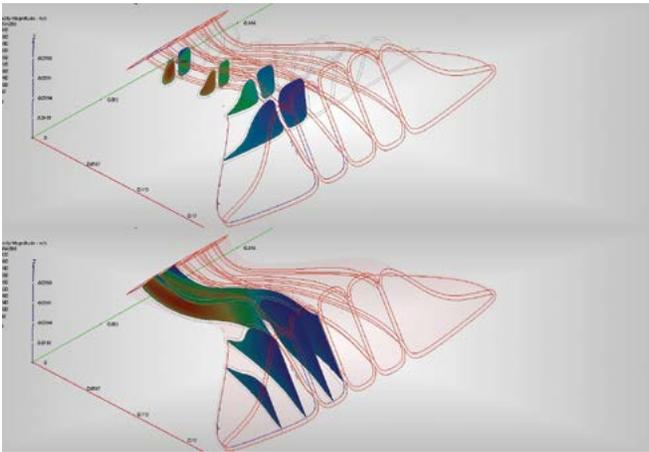
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The flex in the gripper material allowed for seamless flowing along the steel frame. Upon completion of baking, the steel frame simply unbolted and separated from the CFRP shell.

Winding over the reconfigurable frame was an important aspect of the fabrication process (Figure 5). Initially simulated digitally in Rhino 3D, then reproduced through hand winding, the process was completed in three stages: Peak winding, valley winding and spiral winding. Through these operations, several attributes were achieved: Structural rigidity, varying opacities, varied thickness and most importantly, minimal fiber creep and delamination during the winding process. Peak winding was the first stage of winding. Connecting the high points of each frame, this operation created high levels of positive fiber offset. Following, valley winding connected the frame's low points. Pulled with 5 lbs more force, this operation helped pull initial layers into their nominal positions while also equalizing internal tensions. To eliminate delamination, spirals were wound around interconnecting faces drawing in stray fibers. Through a layering of these operations, variation in opacity and texture was also achieved.



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- 4 Frame to CFRP gripper detail.
- 5 String winding study.
- 6 rolyPOLY Confessional on display at the Tyler School of Art.
- 7 Cloud Magnet CFD simulations.

Results

rolyPOLY showed the potential of harnessing CFRP in craft-based monocoque shell structures while maintaining a high level of structural rigidity and winding repeatability (Figure 6). The doubly curved surfaces created through tensile modeling laid a robust structural framework rigid in all orientations. Additionally, rolyPOLY was produced in a minimal amount of time from a continuous material, allowing for the rapid production of both identical and one-off modules. The fabrication process itself also produced virtually no waste. Although many positive attributes are visible through this project, there are several areas that must be further addressed for larger-scale architectural interventions.

Delamination of layers as tension mounts within the overall structure must be further resolved to insure structural and formal consistency. Additionally, further research in methods of

robotic and hand winding will aid in the definition of more robust patterning while ensuring proper fiber placement orientation.

CASE STUDY 2: CLOUD MAGNET

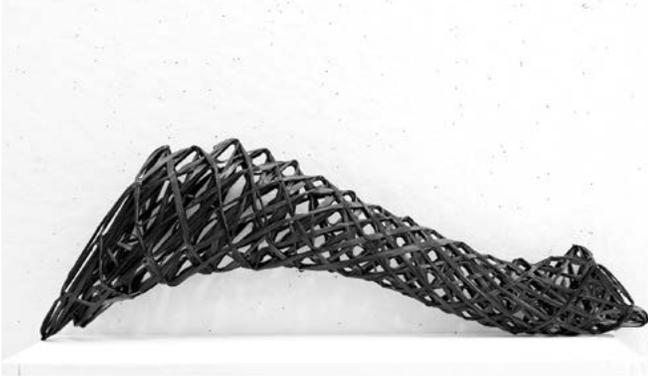
Similar to rolyPOLY, Cloud Magnet also offered the opportunity for one-to-one testing of wound CFRP systems in lightweight, large-scale construction typologies. Cloud Magnet researches the co-dependencies between material, form, energy, and environment through the design and fabrication of a series of environmentally performative kites within the cloud forest in Monteverde, Costa Rica. Cloud forests have been rapidly disappearing due to climate change and deforestation. Rising global temperatures cause a cloud-lifting effect raising the cloud cover above the tree canopy and forest ecosystem that depends on constant moisture and humidity to support its life. The impetus for this project is to explore the ways by which design can contribute to the stabilization of the atmosphere and the restoration of the forest.

In the early stages of research, prototypes focused on the CFRP winding of the kite frames. Prototypes were fabricated at 1/4 scale to test the suitability of the winding patterns in fabricating a strong, yet flexible frame. The full-scale artifacts will measure approximately 12' wide by 8.5' long by 3.1' high. CFRP was selected for its strength to weight characteristics, which meet the specific needs of the Cloud Magnet project while also informing the larger set of research questions previously described.

Methodologies

Initial forms for the Cloud Magnet prototypes were based on Bernoulli's principle of pressure, correlating reduced pressure with increased speed of fluids, such as air. Their forms were derived through, one, the production of venturi tubes directing air from wider into narrower cross-sections; and, two, the aerodynamic lift produced by the flow of air around airfoils, similar to the wings of an airplane, which creates increased airspeed and decreased upper surface pressure on the form. Prototypical designs were evaluated using computational fluid dynamic (CFD) software based on the average and maximum wind speeds. The CFD simulations confirmed the performance of the proposed forms allowing for the development of a fabrication system (Figure 7).

The forces acting upon Cloud Magnet in flight are similar to those acting upon buildings in extreme weather conditions. To deal with these forces, several directions were explored including monocoque shells, rigid diagrid frames (Figure 8), hybridly wound diagrid frames and finally, flexible variable density gridshell structures. Although the monocoque and rigid diagrid structures had an extremely high strength to weight ratio, their lack of flexibility

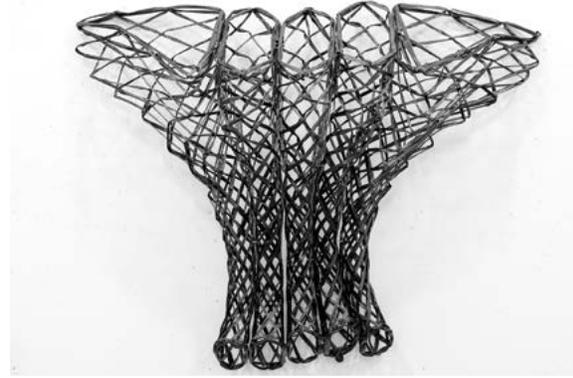


8 Cloud Magnet module V.4.0 winding detail.

could potentially lead to blunt force or fatigue failure over time. Following a series of five completed prototypes investigating these different typologies, a variable density, flexible gridshell structure was chosen. Allowing for levels of programmed rigidity and flexibility within a singular structure, Cloud Magnet's form was now able to better adapt to rapidly changing environmental conditions in flight.

Unlike rolyPOLY, the creation of a vast number of unique prototypes was necessary to satisfy the requirements for flight, stability, the generation of desired internal compression ratios as well as a robust yet flexible structure. For these reasons, a rapidly adaptable, constructible, and disposable formwork was created for 1/4 & 1/2 scale prototyping. Utilizing 1/4" cardboard or chipboard, a unique slicing algorithm and a laser cutter, the project's form was sliced into 15 unique sections with eight additional CFRP grippers, nested and sent for cutting. This workflow allowed for the rapid assembly and testing of a large number of prototypes in a short span of time and for little upfront cost.

Winding of the prototype frame was rather straightforward. Each gripper was numbered between 1–8 beginning on the top of a given section and moving clockwise. Winding began at S1G1 (section 1 gripper 1) and moved clockwise to S2G2 and so on. Upon reaching the final section S15 in one direction, the CFRP shifts one gripper clockwise and continues back towards S1 now shifted one gripper below the original pass. Once eight full rotations in a single direction were complete and all grippers had been filled with a single layer of CFRP, the same process was repeated in a counterclockwise direction, intersecting all previous layers. Variations in this process (i.e. additional passes in one direction, or doubling up every other pass) allowed for the tuning of the artifacts' flexibility. The 1/4 scale prototype iteration of Cloud Magnet consisted of two clockwise layers sandwiching a single counterclockwise layer (Figure 9). Upon completion of the winding process, the artifact was fired and the cardboard was



9 Cloud Magnet complete winding study V.3.0.

simply soaked in water and removed via pliers.

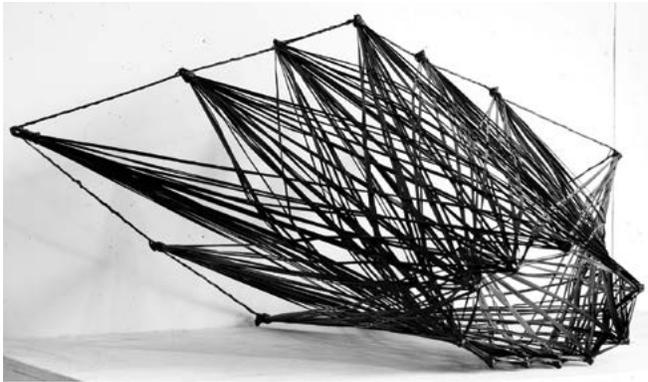
Results

Cloud Magnet showed that composite structures have the ability to be both extremely rigid or flexible depending on winding patterns, amount of material applied, overlap and the desired outcome. The use of simplistic winding patterns helped ensure easy repeatability, constant fiber tension throughout the entire winding process and zero CFRP waste during the entire fabrication process. Additionally, the disposable formwork allowed for the rapid testing of a large number of variables in a short duration of time with minimal costs.

At the same time, several issues need to be addressed before implementation on full-scale architectural artifacts. For small scale prototyping, the disposable formwork is efficient, but in large scale, high-output situations, this method will produce vast amounts of waste. Different methods must be investigated. Additionally, further variable winding investigations should be carried out in conjunction with structural testing to verify its feasibility in long term, high stress environments.

CONCLUSION

Although much more research and prototyping is necessary to realize an architectural-scale prototype, the completion of these two projects within the framework of the "One Day House" illustrates a potential for the further integration of wound pre-impregnated CFRP into the architectural workflow. As demonstrated in rolyPOLY, the ease of use and workability of CFRP allow for not only the creation of complex forms and robust structures, but also extremely tailored aesthetic properties. Initial research in Cloud Magnet also suggests that robust structures could remain flexible, creating the potential for building structures with the ability to slightly adapt to internal and external forces.



10 Cloud Magnet 1/4 scale winding study V.7.0.

Current research has combined the fabrication-process projects into larger prototypes for the Cloud Magnet projects. Rather than working with form first, form is now derived from forces applied during the winding process on a coreless frame (Figure 10). This new series of prototypes has also eliminated most waste while creating robust, flexible and large-scale ($\pm 5'$) prototypes which could be translated to larger architectural installations.

Further transformation of hand winding typologies into numeric winding and robotic programming for robotic coreless winding will also be an important step in bringing this research into the realm of future architectural-scale interventions.

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IMAGE CREDITS

Figures 1–5, 8–10: Andrew Wit, 2015–2016.

Figure 6: Joseph Giampietro, 2016.

Andrew John Wit is the Assistant Professor of Digital Practice within Temple University's Tyler School of Art in Philadelphia, PA. Additionally he is a co-founder of WITO*, "Laboratory for Intelligent Environments" where he creates projects that fringe design, technology and robotics. Prior to his current appointment, Prof. Wit taught courses and led workshops in architecture, urbanism and robotics in both in the U.S. and Japan.

Professor Wit earned his Bachelors of Science in Architecture from the University of Texas at San Antonio, and his Masters in Architecture from M.I.T where he also researched in the Media Lab's "Smart Cities Lab".

Rashida Ng is an Associate Professor and Chair of the Architecture Department at Temple University's Tyler School of Art. Her research and creative activities broadly explore the measurable and experiential characteristics of new material technologies and performative architecture. She has authored numerous papers on these topics and co-edited the book, *Performative Materials in Architecture and Design*, published by Intellect in 2013. Professor Ng is a registered architect in Pennsylvania and the Co-founder and President of SEAMLab, a collaborative think tank dedicated to research and the dissemination of design-based knowledge focused on materiality within the built environment.

Cheng Zhang is a designer in Philadelphia, PA exploring the fecund intersection between performative materials, human experience and the architectural environment. His academic projects and research have been highly recognized receiving awards such as the DaVinci Prize & Temple University's Alumni Thesis Prize. Cheng received his Bachelors and his Masters in Architecture from Temple University.

Simon Kim is a registered architect, and an assistant professor at the University of Pennsylvania, where he directs the Immersive Kinematics research group. As principal of Ibañez Kim, Simon is interested in the augmentation of architecture and urbanism given agency and behavior by new media and material. In support of this project, Simon has worked in both the domains of science and art. He has published numerous papers on robotics and multiagent interaction and is funded by an NSF grant. Simon has also worked with leaders in theater, opera, and dance to develop and test prototypes in the production of culture.