DESIGNING A FOG-HARVESTING HARP

AN INDUSTRIAL DESIGN COLLABORATION WITH SCIENTIFIC RESEARCHERS

Brook Kennedy[1] / Jonathan Boreyko,[2] Weiwei Shi,[2] Mark Anderson,[3] Josh Tulkoff,[1]
Tom Van der Sloot[1]
[1]Department of Industrial Design, Virginia Tech, Blacksburg, VA 24061 USA
[2]Department of Biomedical Engineering and Mechanics, Virginia Tech, Blacksburg, VA 24061 USA
[3]Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061 USA
brook.kennedy@vt.edu / boreyko@vt.edu, svivian@vt.edu, mrkjakob@gmail.com, josht17@vt.edu, tvdrslt@vt.edu

1. INTRODUCTION

It is well known that research universities provide fertile ground for interdisciplinary work between science, engineering, design and other fields. Specifically, in industrial design, faculty and students have the opportunity to translate new discoveries and technologies into useful inventions- for both societal impact and commercial benefit. To date, a great deal has been written about the innovative output and educational value of interdisciplinary collaboration, leveraging applied research, problem solving (McDermott, Boradkar & Zunjarward 2014) and campus entrepreneurship (Etzkowitz, 2000). But, there is also growing evidence that industrial design faculty and students can form worthwhile partnerships with *scientific research* as well, to help develop new technology earlier in the innovation pipeline: through producing lab test mockups, envisioning product applications of discoveries and in helping define research goals early on (Driver, Peralta & Moultrie 2011). Distinct in many ways from the kind of professional industrial design work conducted in the private sector, this "*lab-integrated industrial design,"* for lack of an established term, also provides unique student learning experiences: namely, the industrial design student can be completely integrated from day one in a research program rather than serving a more traditional "translational" role after the fact. For this educational reason along with significant design research output potential, such collaborative, interdisciplinary partnerships with scientific research should not be overlooked, especially in universities with direct access to advanced scientific activity. To demonstrate more specifically what these partnerships can look like, this paper presents a case study of an ongoing, fully integrated lab-to-product development partnership involving the creation of a novel fog harvesting device called "Fog Harp." The invention of Fog Harp was a direct outcome of a close relationship between Professors Brook Kennedy in the department of Industrial Design (ID) and Dr. Jonathan Boreyko in the department of Biomedical Engineering and Mechanics (BEAM) at Virginia Tech. Thus far, eight industrial design students have been able to work on the project from the outset which has enabled three of them to be deeply involved in developing an alpha version of the device. As a result, they have been able to witness the invention process first hand and have been named co-inventors on patent applications and co-authors in scientific publications.

2. FOG WATER HARVESTING: BACKGROUND AND GLOBAL IMPLICATIONS

Fog harvesting is an effective form of safe drinking water collection, endorsed by the World Health Organization (WHO). More recently, it has attracted the attention of scientists and NGOs for use in regions facing extreme water scarcity (UN World Water Report, 2014) (Mekonnen & Hoekstra 2016). As the global population surges and sources of fresh drinking water are strained, finding new ways to improve access to drinking water have never been more pressing. Fog harvesting can play a critical role in this endeavor since fog is often present in some of the driest regions where water alternatives are not available. Overall, arid, coastal regions around the world generally have great success with fog harvesting, including Chile, Morocco, Oman, Eritrea, South Africa, Cape Verde Islands and California. Other inland mountainous areas can also be suitable including Nepal and parts of Appalachia in the eastern United States, where the authors' university, Virginia Tech, is located.

3. ORIGINS OF THE FOG HARP

The Fog Harp project formally began in early 2016 on parallel research paths led by Jonathan Boreyko and Brook Kennedy. Each half of this interdisciplinary team was independently intrigued with fog harvesting. Kennedy in particular, was interested in its potential humanitarian impact and its low-tech simplicity which has only modestly evolved since its introduction. To date, most fog harvesters resemble giant volley ball nets: they are composed of a couple of vertical posts anchored in the ground between which sheets of plastic or metal netting are suspended, with supplemental cables further securing the structure to withstand high winds. As the fog passes through the harvester's sheet material netting, water droplets form on the plastic or metal wires and (in theory) drip down into a cistern or reservoir where it can be collected for use. The process is entirely passive - it requires no energy. Fog harvesters of this basic design were pioneered in the 1980s by Canadian NGO Fog Quest. While aesthetically crude, this design has been proven to work as an "appropriate technology" in communities with limited resources. For these conditions, the design parameters are focused principally on performance and low cost, not appearance. The more drinking water yield the better.

More recently, efforts to improve the basic efficiency of fog harvester mesh materials have been explored by researchers at Pontificia Universidad Católica, Massachusetts Institute of Technology and Technishe Universität München. In addition to improving water yield, these studies have tackled other issues associated with fog harvesting: often the devices need to be delivered to remote locations and must withstand high winds in mostly exposed terrain. Additionally, they must be easily serviceable if damaged, ideally by the local communities that they benefit (Qadir, Jiménez, Farnum, Dodson & Smakhtin 2018). All of these factors are considerations in the development of a successful fog harvester.

Since completing doctoral work in fluid mechanics, Dr. Jonathan Boreyko has had an interest in the behavior of fog water and the limitations of woven cross mesh netting materials. If the netting material density is too open, most of the fog simply passes through without being collected. If the netting material is too dense, it effectively extracts fog water from the air but the droplets get stuck in the netting. When the net gets clogged with droplets, the harvester can't collect more fog- depriving it of optimal efficiency. Analyzing these limitations therefore resulted in the following research question: If the harvester mesh ceases to be productive when clogged with water droplets, how do you keep a mesh from clogging?

3.1 BIOINSPIRED DESIGN INFLUENCE

Both Kennedy and Boreyko also shared an interest in bioinspired design. Having lived in the San Francisco bay area, Kennedy was particularly interested in the natural phenomenon of fog drip which, similar to fog harvesting, enables some types of coniferous trees (including giant Redwoods) to extract moving fog droplets for consumption (Burgess & Dawson 1998). However, unlike the common cross mesh netting used in human conceived fog harvesters, redwoods and other coniferous trees have linear-shaped needle designs (Figure 1) that gather water droplets which eventually fall to the forest floor. There, they are absorbed by the tree and other plants. Empowered with this knowledge, the team wondered: if a closely spaced array of linear geometry like the linear needles of redwood trees could be reproduced, might this overcome the “clogging” problem? Moreover, could such a resulting design also work with the practical site constraints involved in numerous prior fog harvesting installations?

To answer the question, the team adopted a two-part design approach, one scientific the other creative and exploratory. An ID studio project was offered to undergraduate students Josh Tulkoff, Mark Anderson, Luisa Lackasamana, Juhi John and Brian Pughe to investigate the potential construction of a vertical wire array and experiment with ways to improve the aesthetics and usability of the basic volley ball net configuration. Moreover, since many fog harvesting sites contain dozens of harvesters on hills, as with wind turbines in wind farms, their visual impact was considered as well no matter how remote their location. By the project’s end, it was clear how challenging the design task was to balance aesthetics and usability considerations with harvesting performance and cost sensitivity. After considering prior sculptural netting harvesters by other designers to gain inspiration, the team concluded (with the feedback of technical advisors), that few if any presented evidence that they would improve performance or lower costs. As a result, the focus switched to a “bottom up” design approach looking at the material rather than the harvester. Not only were the wire diameter and pitch seemingly critical in harvesting more fog water, but the repetition of these simple elements also promised to have tremendous potential in combining functional, structural and visual benefit simultaneously. Visual cues collected from artists like Gabriel Dawe during the studio project further stimulated future areas of potential visual expression for the wires. Equipped with the knowledge gained from this exploratory exercise, students Josh Tulkoff and Mark Anderson continued with the project as an ID independent study to explore and test the wire arrays. At this stage, the term “Fog Harp” was coined since the essential wire arrays resembled musical harps.

Figure 1: From left to right: linear coniferous needles, linear wires of a miniature test harp. A recent harp pavilion at Twin Peaks, San Francisco by Luisa Lackasamana and a linear twine sculpture by Gabriel Dawe.

At the same time, the team knew that the efficacy of the Harp’s vertical wire array geometry needed to be quantified. Together, the entire team from BEAM and ID worked over the course of weeks to discuss and brainstorm how to produce a harp and scientifically evaluate if it would in fact collect fog water more efficiently than a cross mesh of comparable wire diameter and spacing. To test the hypothesis, Kennedy and Anderson designed and fabricated three 5cm x 5cm miniature harp prototypes. Each miniature harp named H1, H2 and H3 used different metal wire diameters and wire spacing pitches based on recent scientific work led by Gareth McKinley at MIT (McKinley, 2013). All three were constructed with a laser cut acrylic plastic frame with finely cut holes to space the wires at the intended pitches. Two threaded rods with nuts were attached on each half of the miniature harps to tighten the wires (like a musical harp). This also allowed the wires to be tightened after they stretched slightly over time. Next, “gutters” were designed in 3d CAD and 3d printed on a Stratasys Objet printer. These were created to direct the collected water from the wires into a measurement dish. An upper gutter removed water from the area above the wires to a location away from the measurement dish so this collected water would not be counted in the measurement. After the harps were completed, each harp gutter was treated with Rust-Oleum Never Wet water-repellant coating so the water would not stick. Finally, each Harp’s performance was compared with a cross mesh (named M1, M2 and M3) with comparable wire diameters and spacing.

While the miniature test harps were being fabricated, Dr. Boreyko’s lab ordered testing equipment to simulate moving fog which would be aimed at the prototypes to assess their water collecting ability. The equipment included a stream humidifier and an enclosed airtight humidity chamber in which the tests would be performed. Harvested fog water collected in a dish placed underneath the harp (or mesh), whose mass was measured every half hour. After calibrating the testing chamber’s microclimate and debugging the simulated fog spray created by the humidifier, the performance of each harp was tested to surprisingly significant results (Shi, Anderson, Tulkoff, Kennedy & Boreyko 2018). The harp with the smallest diameter wire and closest wire spacing pitch *three-times outperformed* the cross mesh with comparable wire diameters.

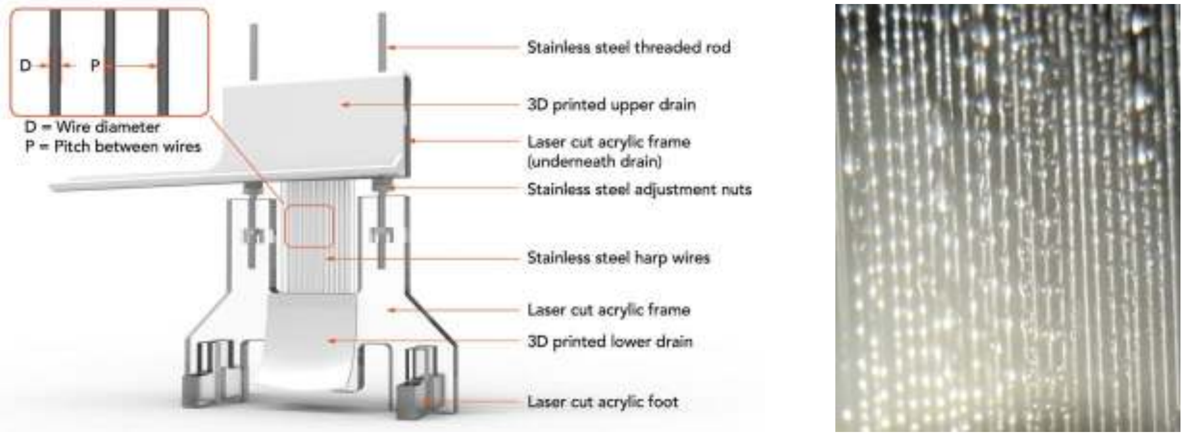

Figure 2: 3d schematic illustration of a laboratory test miniature harp (H1) designed and fabricated for scientific tests. At right, a still image of H1, the harp with the smallest diameter wire and spacing which demonstrated three times water collection efficiency compared with a cross mesh with comparable wire diameters and spacing.

Not only did these results surpass expectations and create tremendous excitement, this data was used to raise additional funding to advance the concept: to design and build a full-scale fog harp capable of harvesting enough drinking water for daily human needs.

4. CONTRUCTING A FOG HARP PROTOTYPE FOR REAL WORLD USE

According to Fog Quest, a substantial fog harvesting site in El Tofo, Chile, with a total harvesting surface of 5000 m^2 yields a yearly average of 3L of water per day per m^2 (Schemenauer, Cereceda & Osses 2005). The El Tofo site is comprised of 100 collectors each with a 50 m^2 harvesting surface that yields in total an average of 15,000L of water per day- enough to support the drinking water needs of a community. Since liters per m^2 is often a standard measure of fog harvesting productivity, the first harp was built with roughly the same dimensions, 1 m^2. From the lab results which observed a threefold increase in water yield, the team projected that the Fog Harp should produce roughly 9L per 1 m^2 on average in the same conditions. This translates loosely to providing drinking water to meet the needs of 2 adults and a child according to the water intake standards defined by the National Academy of Medicine (NAM, 2004). Next, the team sought to substantiate that a full 1 m^2 harp could be produced as a proof of concept and to advance towards building a Harp that could benefit people in the real world.

4.1. CONTRUCTING A PROOF OF CONCEPT 1M^2 HARP

A leading challenge in deploying Fog Harp's linear wire arrays lies in its scalability and mass manufacturability comparable to the site in El Tofo, Chile. While plastic netting and stainless steel cross mesh can be purchased at hardware suppliers in many countries around the globe for fences, mosquito netting and other purposes, sheets of vertical wire arrays are not available off the shelf. In order to create a proof of concept 1 m^2 harp we had to figure out how to produce a custom material. This custom vertical wire array material had to be quickly and cheaply made such that it could eventually compete with the low cost cross mesh alternatives. Surely wire structures could be automated robotically (Oxman, Laucks, Kayser, Nuro-Royo & Gonzalez-Uribe 2014) or perhaps laser cut from sheet metal, but as we mentioned before, these approaches would be costly and require full prefabrication, making them impractical for shipment in the near term. To ensure that the Fog Harp could be impactful for communities needing drinking water, the vertical wire arrays need to be mass produced quickly and able to be knocked down for inexpensive transport, in volume, to the desired location. As a result, development of the full-scale Harp was split into two interdependent design activities: one, to build a "proof of concept" for evaluation of the material system and two, to search for and engage manufacturers in identifying a mass-produced process for creating the critical vertical wire arrays.

4.2. ACTIVITY 1: PROTOTYPING THE HARP AND LEARNING

From here, Kennedy engaged with Industrial Design student Josh Tulkoff to devise a quick means of constructing a 1 m^2 harp by hand. After considering various options, including making two laser cut slotted blocks between which the wires would be wound and pulled taut, the ID team realized that threaded rods available from McMaster-Carr could provide the 'grooves' into which the wires would stay parallel in an array. Later, inspired by the bobbin winding mechanism of sewing machines, the team created a spinning frame to facilitate the winding of the harp's wires (Figure 3).

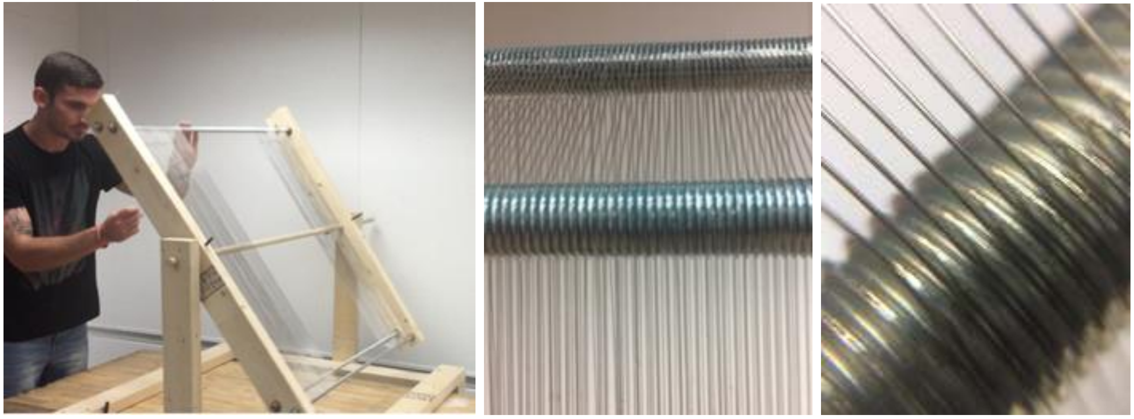

Figure 3: At left, student Josh Tulkoff wiring the first wood harp on a wood spinning frame. At center, a close-up of the stainless-steel wires resting in the threaded rods' grooves. At right, a magnified photograph of the wires resting in the grooves of the threaded rods.

Using two wood 2x4s and four threaded rods, the first crude wood harp frame to support the wire arrays was created. Three of the rods penetrated the 2x4s through holes and were tightened in place with a nut and washer. The fourth rod was fixed in a slot so that later the wires could be tightened if necessary by loosening the nuts, sliding the rod and retightening. Generally, the first Harp wound quickly enough to substantiate to outside reviewers that building a full scale 1 m^2 harp was feasible. It also demonstrated how the material system behaved at full scale. On the other hand, it did not immediately solve the shipment concern but overall it introduced further promising thoughts about mass production.

Now that it was proven that a Harp could be made, the harp's construction was analyzed by professor Kennedy and Industrial Design student Tom Van der Sloot (who joined the project after Josh Tulkoff graduated). With Tom's contributions, a second aluminum harp design using brawnier aluminum u-channel construction and thicker diameter threaded rods was constructed. This harp was produced for demonstration purposes and to document the process to internal funding sponsors. It has also been used for media inquiries and fund raising for subsequent development steps. At present, the project is currently under review for an international museum exhibition scheduled for April, 2019.

4.3. ACTIVITY 2: CONSIDERING MASS PRODUCTION POSSIBILITY

Coincident with the construction of the wood and aluminum Fog Harp prototypes, the team explored possibilities to mass-produce sheets of the wire arrays such that they could be rolled up or knocked for economical transport and overseas deployment. Of the many options investigated, some existing manufacturing technologies showed promise that they could be adapted to produce sheets of the desired wire array design. Other proprietary designs and manufacturing methods continue to be explored. Since the summer of 2018, the team has engaged with manufacturers to mass produce the vertical wire arrays inexpensively. These efforts are ongoing and initial prototypes are expected by early 2019 for evaluation.

4.4. NEXT STEPS FOR FOG HARP

The Fog Harp team's next endeavor is to seek funding to develop the device for on-site testing in three stages. First, as stated before, mass producing the wire arrays on a steel wire loom are in process. Second, when complete, these wire sheets would be affixed to a frame in tension in order to be tested in the Appalachian Mountains where moving fog occurs year around. The full-scale Fog Harp geometry would be tested alongside a control of both steel cross mesh and plastic raschel mesh which has been used widely in the field by NGO Fog Quest for decades. The goal of this exercise is to scientifically evaluate a Fog Harp at full scale to see how it performs compared with existing materials and to verify that it performs as well as it did with the lab tests. A second goal will be to test a second scientific hypothesis- namely that tension of the wires could impact the speed with which the water droplets are purged from the wires. This phenomenon would be tested with video, to understand its mechanics and to hopefully further optimize the Harp's water collection. The third stage of development will be to test multiple 1 m^2 in Harps in existing fog harvesting zones where local communities are in need of potable water. Ideally the same design would be tested in three separate regions- one mountainous, one coastal and perhaps an island location. So far, multiple inquiries to test Fog Harp have been received from NGOs, investors and universities. Additional areas of design investigation will also include exploring improvements to the "volleyball" net form factor used with most fog harvesters, to better accommodate shifting winds, higher winds, efficiency and water storage/ retrieval. To date, there have not been tremendous opportunities yet to improve the aesthetic potential of the device to match the performance improvements, but this will be a priority in the next phase. Concurrently, intellectual property protection is being pursued with the goal of ensuring Fog Harp's humanitarian purpose.

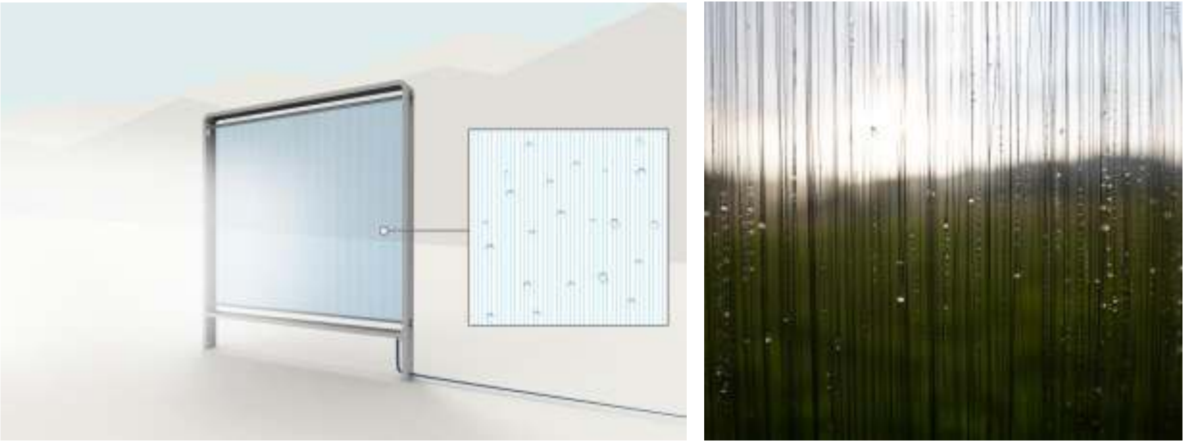

Figure 4: At left, an illustration of an aluminum 1 m^2 prototype Fog Harp with a water pipe to divert collected water to a cistern. At right, a close up of the aluminum harp prototype.

5. CONCLUSION

Overall, this paper has summarized the innovative outcome born of a complimentary partnership between industrial design and scientific research. Without the contributions of BEAM's scientific rigor and resources, the Fog Harp would have never been proven to be a potential breakthrough. Without the creative input, ideation and proof of concept prototyping of ID, realizing this new type of fog harvester would not have resulted. As the project progresses to the stage of full scale field testing, continued scientific testing and iterative design development of the wire material and device will ensue, fueled by the instrumental help of ID students. Collectively, the team is optimistic that the wires will perform well, even in windy conditions– it is also forecasted that a slight fluttering of the wires will be both helpful for shedding droplets but will also be a beautiful spectacle to witness. Whatever comes next, the Fog Harp team will forge ahead to introduce this relevant design where it can achieve the greatest human impact.

Looking forward from these experiences, the authors would encourage others to form similar interdisciplinary teams between scientific research and industrial design, especially in the research university context where there are many opportunities to do so. As this paper has demonstrated, clearly these kinds of early stage "*lab-integrated industrial design*" collaborations offer unique student learning opportunities as well- beyond significant research output. Altogether, the tangible results these partnerships bring should be welcomed and supported.

6. ACKNOWLEDGEMENT

The authors would like to acknowledge the Institute for Creativity Arts and Technology for their support of Fog Harp in its development. The authors would like to acknowledge the ingenuity and hard work of the following students who helped advance the project: Mark Anderson, Josh Tulkoff, Tom Van der Sloot, Luisa Lackasamana, Juhi John, Brian Pughe, Savannah Cranford and Whitney Talbot.

7. REFERENCES

Burgess, Stephen & Todd Dawson. (2004). The contribution of fog to the water relations of Sequoia sempervirens (D. Don): Foliar uptake and prevention of dehydration. *Plant, Cell & Environment*. 27. 1023 - 1034.

Driver, Alex, Carlos Peralta & James Moultrie. (2011). Exploring how industrial designers can contribute to scientific research. *International Journal of Design, 5*(1), 17-28.

Etzkowitz, Henry, Andrew Webster, Christiane Gebhardt, Branca Regina & Cantisano Terra. (2000). The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm, *Research Policy*, 29 (2), 313-330.

Mekonnen, Mesfin & Arjen Hoekstra, (2016). Four billion people facing severe water scarcity. *Sci. Adv.*, 2, No. e1500323.

McDermott, Lauren, Prasad Boradkar & Renu Zunjarward. Interdisciplinary in Design Education. Paper. Austin, TX: Industrial Designers Society of America Education Symposium, Aug. 18, 2014. Print.

National Academy of Medicine, 2004. Dietary Reference Intakes: Water, Potassium, Sodium, Chloride, and Sulfate http://www.nationalacademies.org/hmd/Reports/2004/Dietary-Reference-Intakes-Water-Potassium-Sodium-Chloride-and-Sulfate.aspx Viewed April 12, 2018.

Oxman, Neri, Jared Laucks, Markus Kayser, Jorge Nuro-Royo & Carlos Gonzalez-Uribe. A case study in fiber-based digital fabrication. In Proceedings of the Fabricate Conference, 248–255, 2014.

Park, Kyoo-Chul, Shreerang Chhatre, Siddarth Srinivasan, Robert Cohen & Gareth McKinley. (2013). Optimal design of permeable fiber network structures for fog harvesting. *Langmuir*, 29:13269–13277.

Qadir, Manzoor, Gabriela Jiménez, Rebecca Farnum, Leslie Dodson & Vladimir Smakhtin. (2018) Fog Water Collection: Challenges beyond Technology, *Water, 10, 372; doi:10.3390/w10040372.*

Schemenauer, Robert, Pilar Cereceda & Pablo Osses. (2011) Fog Quest Fog Water Collection Manual.

Shi, Weiwei, Mark Anderson, Joshua Tulkoff, Brook Kennedy & Jonathan Boreyko. (2018). Fog Harvesting with Harps, *ACS Applied Materials & Interfaces*, 10 (14), 11979-11986.

UN World Water Report, 2014. http://www.un.org/waterforlifedecade/scarcity.shtml Retrieved 16, April, 2018.