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Project Title: **MRI: Development of an Urban-Scale Instrument for Interdisciplinary Research**


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The following report was submitted through Research.Gov and has been formatted for public dissemination.

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# 1 Accomplishments

## 1.1 What are the major goals of the project?

1. Adapt Argonne's "Waggle" resilient embedded systems platform for urban installation and for production in quantities of 100s.

2. Purchase and install a network of hundreds of platform nodes in Chicago to operate as a national science instrument, providing (a) open data on urban weather, environment, and activity, (b) opportunity to test, at scale, new sensor and embedded systems technologies, and (c) a programmable environment for in-situ deep learning and other computational and communication capabilities, such as for event or condition detection involving multiple sensors, images, sound, etc.

## 1.2 What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

### 1.2.1 Major Activities:

1. Worked with design and manufacture partners (all U.S. based) to finalize an urban packaging, mounting, and configuration for the first of three planned "waves" of deployment (each wave providing a window of opportunity to insert upgrades, new sensors, etc. (see major research goal 2-b). We are noting and documenting many lessons learned here. Some highlights - our decision to select local (within 1-hour drive from our engineers) companies was critical to debugging many aspects of the manufacturing processes. The four partner companies were selected for (a) circuit board production, (b) metal tooling and parts, (c) tooling and injection molding, and (d) overall design integration and assembly. Proximity was especially important due to other lessons learned debugging the supply chain and assembly processes (see significant results).

2 Worked with City of Chicago and local partners to develop, through a transparent process, governance and privacy policies as well as processes for engaging government, residents, and local organizations (community, businesses, etc.). These were critical to acceptance of a scientific platform in neighborhoods, particularly given the presence of cameras and microphones on the platform.

3. Worked with City of Chicago and manufacturing partners to finalize installation procedures and coordination mechanisms, resulting in a partnership with the Chicago Department of Transportation to assist us in design (electrical safety, mounting efficiency/cost) and installation. Installation tests in August 2017 resulted in an improvement to installation that would decouple the initial wiring (involving underground conduits) from device mounting. This has allowed the city workers to pre-wire locations, reducing the impact of winter freezing on the installation process.

4. Installed the first 6 units in Chicago during August 2016, preparing (see 3) for an additional 60-90 units by end of 2016.

5. Created APIs and data streaming capabilities for hosting of AoT data on the NSF-funded http://Plenar.io platform, the City of Chicago (Plenario-based) http://opengrid.io platform, and an education portal being developed as cost sharing by Microsoft. APIs also support application development, including standard 'trigger' type capabilities such as via the IFTTT API.

6. Completed electrical safety reviews (City of Chicago electricians and, separately, Argonne National Laboratory safety team) and FCC emissions testing. The devices passed the FCC emissions testing, but we nonetheless improved their emissions profile by adding shielded cabling between the control box and Stevenson shield.

### 1.2.2 Specific Objectives:

1. Design a system enclosure and mounting system that would enable initial installation (after wiring is done) and replacement by a single electrician in less than 15 minutes.

2. Engage residents and businesses in Chicago to adopt the instrument as a community asset, where the default posture of the press and many residents is one of suspicion related to surveillance.

3. Develop a partnership and installation procedure with the City of Chicago that will enable the lowest cost installation (cost-share provided by the City of Chicago) and the lowest cost replacement (for future generations with additional features).

4. Test and finalize system manufacture/assembly and installation.

5. Develop data discovery and exploration capabilities to support scientists using AoT data and sharing interpretations of the data (in cases where sensitivity and thus interpreted values vary with other factors such as temperature or humidity).

1.2.3 Significant Results:

0. Gained (and are capturing) a set of fundamental lessons learned (for us and similar projects) regarding the transition of a prototype to a mass-producible device. First, building 20-50 devices in-house is not at all the same as having third parties build devices, where the assemblers need instructions, testing tools for each stage of the build, etc. Second, doing a build of 20-50 devices is not the same as setting up a supply chain to build hundreds of devices over time, where the diverse purchasing lead times, inventory management, unit quality control and tracking, etc. come into play (foreign to academics or other groups accustomed to building a fixed, small number of devices in-house. Lastly, testing manufacturing decisions on small scales is critical. In August our assembly partner recommended removing heat sinks from our single-board computers in order to substitute an aluminum block to transfer heat to the aluminum enclosure given that air circulation heat sink designs would not work inside a small enclosure with no air circulation. We learned after a dozen units were built that removing the heat sinks damaged about 50% of the microprocessors, so we had to convince our supplier (in South Korea, translating through a Korean graduate student) to sell us units without heat sinks (altering their supply chain and Q/A process!). Once this was resolved, we found high percentages of units passing all tests until final assembly. Debugging this revealed that too much pressure was put on the heat sinks (and thus microprocessor), which were intended to press against the enclosure. This caused some to fail, and likely stressed others so that they would be more likely to fail in the field (for instance, when temperatures change rapidly). All of these lessons also indicated that our schedule was too optimistic, not building in time for "debugging" hardware and assembly processes. These will be valuable lessons to carry into the next phase of 200 nodes in 2017.

1. Developed a novel set of agreements and policies for deploying scientific instruments in the public way, factoring public acceptance, privacy, trust/accountability, and governance requirements. These products, along with the insight gained developing them, will be useful to many "smart city" or urban cyber-physical systems projects. To this end we include reports on the process at the project website. This included partnership with the City of Chicago and Smart Chicago Collaborative, as well as over a dozen presentations to various community groups ranging from the Chicago Loop Alliance (one of Chicago's business innovation districts) to the National Association of Realtors to the Chicago Metropolitan Agency for Planning and the Federal General Services Administration (manages 35M sqft of real estate in Chicago).

2. A physical node design and set of procedures for installation of devices, capturing information needed by electricians and minimizing and streamlining both the training/documentation needed and as importantly the potential for miscommunication in the process of installation. A template for installation guidelines has been produced to capture lessons learned here. The design of the node itself, with the goal of quick installation/replacement (upgrade) as well as electrical safety, represents important lessons learned and insight from city workers. In particular, the mounting systems for poles and exterior building walls was designed in collaboration with city electricians. Specifically, multiple design decisions were driven by the goal that replacing (e.g. for later swap-in of upgraded units) units with no more labor time or expense than replacing holiday decorations. This was an important objective, as it means that upgrading the instrument in the future will involve a minimum deployment cost relative to the cost of the equipment.

3. An initial deployment of 6 units in FY16 and preparation for an additional 60-80 by end of CY2016, exercising the installation procedures and communication as well as demonstrating on-board image/sound

processing, system reliability, and remote recovery/programming capabilities. This CY2016 work sets the project up to complete the 500-node deployment by 2018, with multiple options and schedules depending on demand for insertion of new (e.g. experimental) devices. Another result from collaboration with city workers is that the mounting procedures were optimized to allow them to pre-wire locations (install breaker in control panel box, run wire through conduits to pole base), then later to mount the devices (using a bucket truck) and drop a wire down the pole to tie in at the base. Breaking installation into these two pieces makes winter installation more feasible (when the ground is frozen, water in conduits would make the ground wiring impossible). We thus hope to reach 100 devices by February 2017 before switching to upgraded designs for the 200 units to be deployed in 2017.

4. Multiple working group discussions among scientists assisting in selection of the first 100 locations for deployment, supporting funded research from NSF, NIH, DOE, and other agencies and scientists from UChicago, UI-Chicago, Northwestern, UIUC, Northern Illinois University, Notre Dame, Purdue, and others.

5. Held a "disruptive sensors" workshop to begin to engage sensor research community, including industry and academia, in order to develop a roadmap for the platform in 2017 and 2018. For instance, we have identified several projects aiming to move from research to commercial production of particle sensors costing $5-20 rather than $400 by 2018. Participants in the workshop included academics from multiple universities, scientists from national laboratories including Argonne and Wood's Hole, representatives from industry (Intel, SPEC, Bosch, etc.), and participants from public agencies and foundations including Cook County Environmental Management Department, U.S. EPA, NASA, and the Robert Wood Johnson Foundation. Participants were eager to adopt the AoT's underlying Waggle platform for extensions and pilot projects. For example, the City of Portland will pilot units in early 2017, with interest in working with computer scientists to develop image classifiers to discern whether bike share riders are more or less likely to wear helmets than those riding private bikes.

6. Began developing cost-sharing plans with each of the six original companies, while adding AT&T as a communication partner. This includes an education portal being developed by Microsoft and development of new gas sensor boards by Intel, whose cost sharing already exceeds their original commitment. (See training/professional development below for Motorola cost-share activities).

#### 1.2.4 Key outcomes or other achievements:

AoT has captured the imagination of the science and policy communities, with an increasing rate at which cities and/or universities are inquiring about pilot projects. To date over 50 requests have been received to test units in other cities around the world, or by research teams interested in using the platform for their research.

Through U.S. IGNITE we were introduced to Professor David Lary from the University of Texas-Dallas, whose NSF CISE/CPS-funded "Geolocated Allergen Sensing Platform (GASP)" whose project was in need of a more reliable platform that could be produced at scale. GASP has adopted the AoT's Waggle platform (in a simpler rooftop deployment packaging) and in turn AoT adopted the Alphasense particle sensor. Moreover, Lary's team had worked with Alphasense to modify the firmware of the sensor to report a histogram of 1-100-micron particles rather than the standard firmware that reported only PM 2.5 and PM 10. Finally, this collaboration has produced a growing community of air quality scientists who have agreed to collaborate on evaluation and quality assurance processes for AoT air quality sensors.

### 1.3 What opportunities for training and professional development has the project provided?

The project has involved summer student teams working at Argonne and University of Chicago on systems, software, and data access projects.

Funding from cost-share partner Motorola enabled out collaboration with the School of the Art Institute of Chicago and Lane Tech High School, a charter High School in Chicago, where we piloted an 8-week Data/Sensor-driven science curriculum with 150 students in Spring 2016. This curriculum is being repeated in Winter 2017 with a goal of developing materials for other schools to adopt the curriculum.

## 1.4 How have the results been disseminated to communities of interest?

Extensively through the project website and the media, including access to reports on community engagement and transparent policy development, project policies, project technical details, and science and education goals.

## 1.5 What do you plan to do during the next reporting period to accomplish the goals?

Per the objectives above:

1. Design a system enclosure and mounting system that would enable initial installation (after wiring is done) and replacement by a single electrician in less than 15 minutes.

This goal has been met, but we believe improvements can be made to the manufacture/assembly process both to lower the cost per unit. Initial units have a base cost, including assembly, of roughly $1500 with two more expensive sensor options that can be deployed on a % of units while keeping the average cost below the budgeted $2000 per unit.

2. Engage residents and businesses in Chicago to adopt the instrument as a community asset, where the default posture of the press and many residents is one of suspicion related to surveillance.

This goal is an ongoing one, but our initial progress has been hard-fought and successful. After several misleading press reports about privacy, our transparent approach and community engagement through public meetings have dispelled the privacy concerns that we have encountered.

3. Develop a partnership and installation procedure with the City of Chicago that will enable the lowest cost installation (cost-share provided by the City of Chicago) and the lowest cost replacement (for future generations with additional features).

This goal has been largely met, in that after the initial wiring we have a system that can be replaced in 15-20 minutes by a crew of two with a bucket truck. We believe we can further improve as we get more experience working with the crews. Further, we will be exploring additional placement strategies such as on building exteriors and rooftops (to get more data in the vertical axis and to ground partnerships with public libraries and schools) and on moving platforms such as city buses and trains.

4. Test and finalize system manufacture/assembly and installation.

Our current process is limited to 10 units per week. We are looking at alternatives to improve this rate for two reasons. First, the demand for pilot projects is increasing and the only way to meet that demand up and above the 500-unit Chicago instrument is to produce units at a higher rate. Second, a higher rate means we can compress manufacture calendar time in order to leave more room for engineering efforts aimed at improving reliability and introducing new sensors or more powerful computing capability.

5. Develop data discovery and exploration capabilities to support scientists using AoT data and sharing interpretations of the data (in cases where sensitivity and thus interpreted values vary with other factors such as temperature or humidity).

We will be releasing API documentation and initial data in mid-October 2016. We will be working with the science community this year to improve the APIs and portal capabilities, while also continuing to work with the growing number of companies and research partners who are planning to develop portals and analysis tools for the AoT data streams.

# 2 Products

## 2.1 Journals or Juried Conference Papers

P Beckman, R Sankaran, C Catlett, N Ferrier, R Jacob, M Papka (2016). Waggle: An Open Sensor Platform for Edge Computing. Proceedings of IEEE Sensors 2016.

Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; OTHER: Conference ID: 34402X

## 2.2 Audio or Video Products.

NSF produced a 3-minute "Science Nation" video about AoT, to be released in late 2016.

## 2.3 Websites

### 2.3.1 City of Chicago Public Engagement Report

http://arrayofthings.github.io/engagement-report.html

Report detailing public engagement efforts, goals, and results. Public engagement objectives were to inform residents about the instrument goals and capabilities, discuss privacy concerns, and provide details on policies. An overarching objective was to position the instrument as a community "asset" as distinct from a sterile device or a surveillance program.

### 2.3.2 FAQ on Privacy and Policy and Feedback

http://arrayofthings.github.io/policy-responses.html

Exhaustive (regularly updated) FAQ that addresses all of the public comments and suggestions, initially taken from public meetings, email, web forms, and multiple online options for commenting on draft policies (including the OpenGov Foundation's Madison site).

### 2.3.3 Node Location Request

https://docs.google.com/forms/d/e/1FAIpQLScIG6YevqzWW4d1U0eH1D2tNSQuHnlng6AMrlDE4V8Gf136qQ/viewform

Form for use by residents or others requesting that AoT place one or more nodes in a specific location or neighborhood. Allows a non-scientist to articulate a science question in terms of goals, type of measurement, and locations.

Note this form is linked from the friendlier URL of the main project site, http://arrayofthings.us

### 2.3.4 Plenario System Overview

https://github.com/UrbanCCD-UChicago/plenario-stream/wiki/System-Overview

Extensive system documentation for the Plenario system that will serve as a key portal for all AoT instrument data. The site is necessary to support developers wishing to create portals, analytics tools, or applications that use instrument data.

### 2.3.5 Project Information Portal

http://arrayofthings.github.io

Main project website with links to all policies, technical documentation, press, etc.

### 2.3.6 VIDEO: AoT Overview

https://www.youtube.com/watch?v=BHrslIHJHeo&feature=youtu.be

Short video explaining the science and policy goals of the instrument, the technical capabilities, and some of the expected outcomes.

2.3.7 VIDEO: AoT Technology and Privacy

https://www.youtube.com/watch?v=pFL5QNwgs6A

Short video focusing on the manufacture, technology, and privacy of the AoT instrument. The video was developed specifically to help residents understand the privacy protections built into the device and into policy.

2.3.8 Waggle Platform Software Site

https://github.com/waggle-sensor/

Developed site to document the open source software stack, and eventually the hardware specifications, for the instrument. This site is also essential to engaging the research and development community in evaluating and hardening the software stack.

# 3 Impacts

## 3.1 What is the impact on the development of the principal discipline(s) of the project?

There are several areas of impact of note during this first year. First, we have discovered a tremendous demand for a general purpose, reliable sensor and embedded systems platform in the science community. Beyond the AoT project, for example, we have assisted several other teams in their adoption of the underlying Waggle platform used by AoT. One project of note is the "GASP: Geolocated Allergen Sensing Platform" (NSF Award CISE/CNS 1541227), which adopted the Waggle platform for deployment on rooftops in Chattanooga, TN (PI David Lary, UT-Dallas). This collaboration also provided the AoT project with an excellent recommendation on particle sensors, and indeed the AoT project has adopted modifications made by Lary's team to the Alphasense particle sensor, expanding the AoT sensor package.

With the accepted publication about the Waggle platform we also contribute to areas ranging from reliable embedded systems to computer vision (in that the platform runs standard libraries, ultimately offering computer vision experts an urban-scale computer vision instrument with 1,000 cameras).

## 3.2 What is the impact on other disciplines?

The AoT project co-investigators and senior personnel lead disciplinary science teams. Outside of computer science, we see impact on each of these other areas. Co-I Kathleen Cagney (UChicago) leads a social sciences team, and interaction with this community has reinforced the importance of embedded computer vision, for instance to detect subtle conditions or events ranging from measuring the "stickiness" of a place (how it is used by individuals and groups of pedestrians) or looking for indicators related to public sentiment (people walking babies or dogs represent data about how residents feel about safety). Senior personnel Rob Jacob (Argonne) has engaged the atmospheric, environmental, and air quality communities who helped to inform priorities on the AoT system design, for instance the addition of an upward facing camera as well as IR and UV sensors. Co-I Daniel Work (UIUC) helped to guide the use of cameras trained on intersections, including the need for the privacy policy to allow for collection of training images.

We also note that the privacy approach to the project, we believe, will set an important example for the use of cameras to support science while respecting privacy. Of particular importance is the general strategy of specifying an exhaustive list of data than can be extracted from images, in contrast to traditional policies that specify an exhaustive list of what CANNOT be done with images. By embedding computer vision and AI in the platform, we are able to develop policies where residents or other observers know at all times what information is being collected and why. Traditional policies that focus on what cannot be done with images essentially leave open the question of what CAN be done (an infinite set). This area is one that will evolve;

however, our engagement of experts and the general public has set a solid stage for evolution and improvement of the policies in partnership with city residents and stakeholders.

## 3.3 What is the impact on the development of human resources?

Senior personnel Douglas Pancoast (School of the Art Institute of Chicago) and Kate Kusiak Galvin (UChicago) leveraged AoT to obtain a grant from the Motorola Foundation to develop and teach an IoT curriculum at a local charter high school. The 8-week curriculum was taught to 150 students in spring 2016, with students working in groups of 3 to (a) design an experiment, (b) design a sensor-based data collection instrument, (c) build and install the instrument, and (d) analyze the data. The project was given follow-up funding by the Motorola Foundation in order to develop faculty curriculum and to teach the course a second time in spring 2017.

The project also employed undergraduate and graduate students in 2016, working on various aspects of the platform - from hardware design to database software development - under supervision by project principals.

Test deployments with 6-10 nodes are being installed at Northern Illinois University (Co-I Mike Papka), University of Illinois-Chicago (Engineering Dean Peter Nelson), University of Chicago (CS department chair Mike Franklin), and University of Washington (Bill Howe working with Seattle CTO Michael Mattmiller). These test deployments will give students and faculty the ability to innovate with the software and hardware, with nodes being located in such a fashion that allows for students to access the nodes (e.g. to add sensors and re-install).

## 3.4 What is the impact on physical resources that form infrastructure?

We are documenting the interactions and lessons learned from working with the Chicago Department of Transportation on the final physical design and installation procedures. Already this collaboration influenced the mounting hardware design such that, once initial wiring is done, a unit can be replaced in the same amount of time as installing a holiday decoration on the city pole. The installation is also creating a citywide "harness" in that dedicated power circuits are being installed for each node, using standard NEMA outdoor-rated screw-connectors, so that future nodes can be deployed. The use of a dedicated circuit also makes each node effectively a "probe" that can provide power quality and reliability data (to this end we obtained funding from the Dept. of State through DOE to add a "last gasp" and power quality sensor to the package in 2017).

## 3.5 What is the impact on institutional resources that form infrastructure?

The project has resulted in a close and collaborative partnership not only with the relevant executives (deputy mayor, commissioner of transportation, CIO, etc.) but also with the entire management chain from Deputy Mayor to union electrician. Each of these layers of organization (seven total) have grasped the importance of the project and become champions. This has important impact on the view of science from within city government, and in turn the Chicago "story" impacts how other cities view such projects. To illustrate the partnership, we learned from the electricians that they had selected a different pole than we specified at a particular intersection and hoped that this was OK. They reported that the notebook we provided them, with Google Streetview images, used wintertime images. Consequently, they noted that nearby trees would obscure the view from the upward facing camera and relocated the device to the opposite corner. *The fact that the union electricians understood the goals to this level was remarkable and unexpected*.

## 3.6 What is the impact on information resources that form infrastructure?

By piggybacking on the NSF-funded Plenario system (http://plenar.io) we are able to integrate sensor data with other urban data, such as 311 calls, crimes, permits, or inspection data.

### 3.7 What is the impact on technology transfer?

A significant consequence of the unexpected demand for pilot projects has been a series of discussions with the University of Chicago and Argonne regarding the best way to scale the production and support of the technology while minimizing any distraction from the AoT project in Chicago. Initially we have created a service center (often called "cost recovery center") at UChicago to facilitate agreements with other institutions in order to support the financial transactions associated with purchasing nodes for pilots. We expect that there will be a need for a service company to be formed in 2017 and are discussing this with the University and Argonne (where the underlying Waggle platform was developed).

### 3.8 What is the impact on society beyond science and technology?

We find that our public interactions as well as both critical and laudatory press have raised the profile of science related to "smart cities" and have encouraged interest on the part of the general public and students in Chicago. Evidence to this end is the increasing volume of contacts from individuals in the community and from schools, libraries, and community groups who have interest in using the data from AoT.