How can innovative 3D printing technology be used to help provide low-cost surface atmospheric observations in under-developed data-sparse regions?

In many regions of the world, surface weather stations are sparsely distributed and/or of poor quality. Existing stations are often sited incorrectly, badly maintained, or have limited capacity for real-time monitoring. In developing countries, the lack of resources to acquire and deploy instrumentation and the lack of training of local weather service staff to properly site, calibrate and maintain the equipment, amplify the issues of poor-quality observations. Because commercially available meteorological instruments are relatively expensive, those that fail – or are stolen – are often not replaced. The result is that weather observations in critical regions are not available after such events.

The US National Weather Service (NWS) International Activities Office, along with the University Corporation for Atmospheric Research/National Center for Atmospheric Research (NCAR), and with support from USAID, has established an initiative to develop and deploy low-cost weather instrumentation. The intent is to provide observational technology to enhance environmental monitoring, which will improve the quality and availability of data needed for applications such as early warning alert systems. To meet the needs for improved and consistent meteorological observations, the goal of this project is to “develop new, inexpensive technology and provide it to weather services in developing countries so they can build, deploy and maintain their own surface observation network.”

Instrumentation has been designed for this initiative using new technologies such as 3D printers, Raspberry Pi computing systems and wireless communication.

The project team has been beta testing initial versions of a 3D-printed automatic weather station (3D-PAWS) since June 2014 at the NCAR Marshall testbed facility in Boulder, Colorado. An additional site has been instrumented at the NOAA test facility in Sterling, Virginia, since December 2015. At both sites the 3D-PAWS sensors are being evaluated relative to observations from high-quality, well-calibrated commercially available reference sensors. Additionally a
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“Currently five 3D-PAWS sites are operational in Zambia, and installation of an additional five sites is planned for September or October 2016”

SYSTEM OVERVIEW

The current design of the 3D-PAWS is shown in Figure 1 (NOAA testbed site). This configuration consists of a three-cup anemometer, wind vane, tipping bucket rain gauge, and temperature, relative humidity and pressure sensors. The system is designed to be adapted and installed on a variety of frames. The system configuration is designed to use local materials to create the weather station tower, depending on what is readily available for a reasonable cost.

For the testbed installations and the Zambia pilot study, galvanized iron pipe was used for the tower framework. However, aluminum, PVC pipe, and/or wood framing can be used. Sensor operation, communication and data archiving are controlled using a low-cost Raspberry Pi computer running a version of Debian Linux. The Raspberry Pi computer is housed in a waterproof unit mounted on the frame. Power for the 3D-PAWS can be supplied from the grid (5V is required as input) or a battery with solar power backup. The sizes of the battery and solar panel will vary according to the location. Power consumption is currently being evaluated and optimized, but the requirements are relatively small. Data can be transmitted with a direct network connection, wireless adaptor, or cell-modem setup.

Several additional sensors are currently under development. Solar radiation, lightning detection and soil moisture/temperature sensors are being designed for future deployment. Initial research has been conducted into adding capabilities for stream flow/stage, air quality and visibility monitoring.

The initial cost to set up a 3D-PAWS printing system is about US$5,000. Each station thereafter costs between US$300 and US$600 depending on options for power and communications. Depending on the communication requirements, the cost could be minimal for wireless communications.

One unique aspect of the 3D-PAWS design is that all the housing, connectors and wire harnesses are created using a 3D printer. For each station about 120 components are 3D printed. The designs of the components were created using open-source CAD software. Examples of the designs for the radiation shield, tipping bucket rain gauge, three-cup anemometer and wind vane are shown in Figure 3. A project goal is to make these designs open-source so that other institutions and educational programs can use and adapt them to meet their needs in terms of research, operations and/or education and outreach.

CALIBRATION AND DATA QUALITY ASSESSMENT

The sensors on the 3D-PAWS were calibrated in a controlled environment before field testing began. The temperature, pressure and relative humidity (RH) sensor calibration test results were all within the manufacturer’s specifications in the laboratory. The tipping bucket rain gauge had less than 5% error for simulated rainfall rates of 0.1-30mm/h. The three-cup anemometer and wind vane sensors were tested and calibrated in the wind tunnel at the NOAA testbed facility (Figure 2). Each three-cup anemometer was calibrated using the wind tunnel; the tests indicate that the calibration is very consistent over a large range of wind speeds. Stress
Low cost weather instrumentation

The comparison of 3D-PAWS temperature with the CS500 reference sensor indicates good performance within the observed temperature range of 10-37°C

The comparison of 3D-PAWS temperature with the CS500 reference sensor indicates good performance within the observed temperature range of 10-37°C. There is minimal scatter in the comparison and the root-mean-square error (RMSE) is 0.4°C. The comparison suggests little to no bias as a function of temperature. Relative humidity comparison results indicate larger variability in the comparison. The RMSE for RH is 5% over the range of observed values from 10% to 90%. The bias at low RH values is high (~10%). There is a low bias observed (~10%) at high RH values. The mid-range of RH shows a minimal bias. These results indicate that the dynamic range of the 3D-PAWS RH sensor is smaller than that of the CS500 reference. The estimated uncertainty for RH is likely to be acceptable for many applications. However, other low-cost RH sensors are currently being tested to determine if they offer a better performance.

The 3D-PAWS pressure comparison with the Vaisala PTB101B sensors indicated that the sensor is well calibrated. The results indicate minimal scatter within the range of observed station pressures. The RMSE for the comparison is 0.5hPa. One limitation of the 3D-PAWS pressure sensor is that the resolution is less than with the Vaisala reference. Wind speed results show that the 3D-PAWS three-cup anemometer is well-calibrated on average for consistent wind speeds, but there is considerable scatter in the comparison (RMSE = 1.8m/s). Visual inspection suggests there is a slower spin-up/
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As climate change intensifies, bringing more extreme weather as well as seasonal and longer-term changes, effective adaptation for rural regions will depend on timely and accurate advanced meteorological information. Early weather warnings will enable farmers to plan ahead and shelter their animals and protect their income and families. In addition, the collection and distribution of local rainfall information can help smallholder farmers to adjust their crop production methods to changing seasonal precipitation patterns.

Since 1997, USAID’s Office of US Foreign Disaster Assistance has been partnering with NOAA to improve the observation, prediction and communication of risks associated with hazardous weather in developing countries. The Zambian government has been one of the first in Africa to recognize this need for improved observation and prediction. The initial project, RANET (Radio and Internet for the Communication of Hydro-Meteorological Information), partnered with the ZMD to work with rural communities to collect regional climate information. This information has been used to develop a rural early-warning system by communicating potentially hazardous conditions through partnerships with rural community radio stations. The 3D-PAWS project builds on this initial project. The goal is to implement 3D-PAWS sensors to extend the observation network and to develop new decision-support applications using the more extensive observation network. Ultimately the project is focused on building capacity in Zambia and other underdeveloped countries to reduce weather-related risk.

As part of this initial effort, five 3D-PAWS systems were successfully installed during a February-March 2016 field deployment, including measurements of pressure, temperature, humidity, wind speed, wind direction and precipitation using battery/solar power sources. Communications were configured to use either cell modem or wireless devices. The post and tower for securing the battery and solar panel were developed using local materials and built at a local shop in Lusaka. For the pilot study, the 3D printed components were made in the USA and taken to Zambia. For the next deployment, the plan is to have most if not all the 3D printed components made at the ZMD.

NEXT STEPS

The plan is to continue to observe the network in Zambia over a period of several years. The goal of 3D-PAWS is to transition the technology to the ZMD. During the next phase, training will be conducted to teach ZMD staff how to print and assemble the components of the weather station. Training on how to configure and maintain the Raspberry Pi, sensors and communication components will be provided to ZMD staff. At the end of the next phase, they should be making their own 3D-PAWS, with the plan to expand the observation network by 50-100 sites in the next two to three years. Efforts are ongoing to establish additional networks in other data-sparse regions in Africa, Asia and central America.

Additionally, observations being collected at the testbeds and in Zambia are continually being evaluated to establish data quality standards for different climatic conditions. New sensors are being developed and tested for future deployment. New development includes soil moisture and temperature, solar radiation, lightning and streamflow/satellite sensors. As part of the 3D-PAWS initiative, comprehensive documentation and training material is also being developed and will be distributed with the sensor designs when the system becomes available to the community.

A near future step of the project is to demonstrate the usefulness of 3D-PAWS observations in the development or improvement of hydrometeorological applications. The plan is to implement a regional weather research and forecast system over Zambia using cloud computing resources. Observations from the 3D-PAWS network will be assimilated into the WRF system in real time. The goal of the planned study is to demonstrate that the observations can be used to improve weather forecast products in a data-sparse region.

In the future, the implementation of 3D-PAWS networks could support other applications. For example, real-time monitoring of precipitation in ungauged or minimally gauged river basins would provide input to flash flood guidance and early-warning decision-support systems for communities at risk of flooding. Water resource management tools could take advantage of a network of 3D-PAWS stations to improve the operation of reservoirs for fresh water supplies and the generation of hydroelectric power.

There are several possible agricultural applications. For example, operation of irrigation systems could be optimized using surface and soil (planned for the next phase of 3D-PAWS) observations to maximize crop growth and minimize water use. Protection of farmer’s livelihoods could be improved through better monitoring of stressful conditions of crop conditions. There are even potential health benefits through improved monitoring of conditions that could lead to outbreaks of diseases such as meningitis and malaria. These are just a few examples of applications that could be developed or enhanced with the implementation of low-cost observation networks such as 3D-PAWS.
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