Evaluating 3D Printed Alternatives to Weather Monitoring

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Abstract
The University of Atmospheric Research (UCAR) launched its 3D-Printed Automatic Weather Station (3D-PAWS) initiative, a project designed to collect meteorological data at a lower cost than a conventional weather station. The goal of this product was to produce a 3D-PAWS system to test the usability and reliability of the system. The problems encountered during production were documented and used to make suggestions to improve 3D-PAWS before widespread deployment to improve meteorological data coverage in currently underrepresented regions.
Acknowledgements
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Executive Summary

Introduction
Weather data monitoring has crucial importance to a wide range of economic, environmental, civil protection, and farming activities. Weather monitoring is also important in providing data for models that enable society to predict future changes in the environment. Demand for these data has been increasingly met by the deployment of automatic weather stations.

In 2016, The University Center for Atmospheric Research (UCAR) began an initiative to produce a low-cost 3D printed automatic weather station (3D-PAWS). In an attempt to aid in expanding observation networks, UCAR began the 3D-PAWS initiative with the goals of: building capacity to reduce hydrometeorology-related risk in developing countries, observing and communicating weather and climate information to rural communities, and developing observation networks and applications to reduce weather-related risk. The goal of the 3D-PAWS program was to produce a “very high quality surface weather station [that] can be manufactured in about a week, at a cost of only $200-400”. The system was designed to measure pressure, temperature, humidity, wind speed and direction, precipitation, and radiation using low-cost sensors. Low-cost stations could be used to improve access to weather data in underrepresented regions for improving local forecasts and recording global climate trends.

The goal of this project was to replicate the 3D-PAWS system supplied by UCAR and compare the system to a commercially available weather station. By comparing a 3D-PAWS system to a commercial weather station, and the time and cost disparity of assembling and installing both stations, suggestions for changes to the 3D-PAWS project, and potential use cases were identified.

Background
Weather and climate are distinguished by their temporal and geographical scales. Weather is the fluctuating state of the atmosphere, characterized by rapidly developing and decaying weather systems with limited predictability. Climate varies over a greater time scale and refers to the average weather and its variability over a timespan and area. Weather varies over hours and days, while climate varies over years and decades. Weather and climate monitoring rely on quantitative observations, which can be input to computer-based models for forecasting. These meteorological data can be applied to risk assessments, hydraulic design, crop water-use estimates, irrigation scheduling, and input variables for climate change models.

Weather data are commonly collected by automatic weather stations (AWS), meteorological stations at which observations are made and transmitted—sometimes referred to as commercial or professional weather stations. During the last two decades, the number of AWSs has greatly increased as a consequence of the need to provide meteorological data in near-real time.

Because this project focused on 3D printed components, it was necessary to develop an understanding of the print process. The required print material was specified by UCAR, however, background research on 3D printing had to be done. The information acquired during preliminary research was used to develop initial printer settings for producing the components of 3D-PAWS.
Methodology
To assess the assembly and installation process of 3D-PAWS the following objectives were established:

1. Establish a technical and practical understanding of 3D printing methods.
2. 3D print, assemble, and install 3D-PAWS.
3. Determine a suitable location for installing 3D-PAWS and compare performance with a commercial weather station.
4. Perform a cost analysis of 3D-PAWS.

Objective one was met by establishing a practical knowledge of 3D printing techniques and methods before printing 3D-PAWS components. This was accomplished through background research and testing printer settings. Trial print runs were conducted to determine the thermal properties of the printing filament and necessary printer settings such as bed temperature, extruder temperature, and print speed.

Objective two was to print and assemble the 3D-PAWS system. All 127 components were printed using the specified acrylonitrile styrene acrylate (ASA) filament using a Flashforge Creator Pro 3D printer. This was accomplished by separating the components into thirty-seven print runs, which consisted of component groups that would fit on the physical dimensions of the 3D printer. During the printing and assembly process, any difficulties encountered with assembly instructions or the physical components were noted and conveyed as recommendations to UCAR.

Objective three was met by installing and observing the 3D-PAWS adjacent to a commercial weather station. Initially, installation sites were proposed based on the World Meteorological Organizations guidelines for weather station siting. Due to access issues to the proposed site, the two stations were installed at a Worcester residence. Though this site was not perfectly representative of the Worcester region, the stations were located close enough to each other to allow direct comparison of the data collected.

The final objective was met by performing a cost analysis of printing and assembling the 3D-PAWS station. The cost of all materials, components, and tools purchased for this installation were recorded and used to assess the total final cost.

Results and Discussion
A proposed benefit of 3D-PAWS was that it could be assembled in one to two weeks. To assess this claim, the total time of printing and assembly was recorded. The total printer runtime for printing every 3D-PAWS component was 221.43 hours. Assuming that the printer had been run continuously, it would have required just over ten days to print the components. Given the physical constraints of the 3D printer’s bed, and limitations to how quickly ASA plastic can be printed, there are no print settings that could be modified to decrease the amount of time spent printing.

After completing the assembly, the 3D-PAWS system was installed in the backyard of a house in Worcester, MA. 3D-PAWS was installed directly adjacent to an AccuRite 01024 Pro Weather Station. After installation, the two weather stations were observed. The most notable observation made was the difference between the anemometers. While the AccuRite anemometer spun freely in even light
breezes, the 3D-PAWS anemometer was never seen spinning. The 3D-PAWS system reported data to the internet portal for 52 hours after installation, but then stopped reporting for an unknown reason. Because data acquisition was so unreliable, no data accuracy tests were conducted.

This project began under the premise that it would cost between $200 and $400 to produce a single 3D-PAWS system. In addition to evaluating the assembly and installation process of 3D-PAWS, this project also served to assess the cost of the project. The true cost of producing a 3D-PAWS system was calculated by tracking expenses throughout the assembly process. The final cost of producing and installing 3D-PAWS at WPI was $698.87, significantly larger than the advertised cost. The constraints of production should be considered when presenting an estimated price, or the price estimate should be updated to reflect the cost of all necessary tools and materials.

**Recommendations**

In this chapter, specific recommendations to further this project were included. These recommendations addressed issues encountered during assembly or changes that would improve future 3D-PAWS installations. These recommendations most importantly include potential revisions to the assembly documentation, assembly process, and software. Recommendations were broken down into the following sections:

**Printing**
- 3D printer settings should be provided to minimize test prints
- An explanation of how the system could be completed in two weeks should be included
- 3D printing seemed unnecessary for many of the small parts.

**Cost**
- The UCAR website suggests a 3D-PAWS installation would cost between $200 and $400. This cost breakdown should be provided to potential users

**Purchased Components**
- Several components were not specified in the assembly document, which made sourcing them difficult. Other components did not function properly.

**Wiring**
- A schematic of the wiring sections should be supplied to make for a clearer assembly process as the step-by-step pictures are confusing to follow.

**Sensor Software**
- The sensor software was not well documented and difficult to set up with the internet portal. Better documentation should be provided, and the software revised for easier user setup.

**Conclusion**

While the 3D-PAWS system produced during this project did not fall within the time and cost constraints provided by UCAR and NCAR, low-cost weather systems have potential for future applications. Low-cost weather stations could be implemented in regions without previous access to localized weather data and improve local forecasts and record global climate trends. If it were possible to build and assemble a system within UCAR’s time and cost total recommendations, the 3D-PAWS initiative could be a viable alternative to using commercial weather stations to collect meteorological data. This project can potentially inform future users on how to assemble low-cost weather stations in the most efficient way possible.
Authorship Statement
This page details the sections that each student worked on in this report.

Rachel Santarsiero was primarily responsible for the drafting of the Introduction, Background, Professional Licensure Statement, Design Statement, Conclusions, and Recommendations. She assisted in drafting the other components, and jointly made edits on all sections with David. She assisted David in producing the 3D-PAWS components and the commercial weather station. She also worked with David to install the weather stations and collect the meteorological data each station collected.

David Smallwood was primarily responsible for drafting the Methodology, Results and Discussion, and contributed to the Background, Conclusion, and Recommendations and Areas for Future Study. He jointly made edits on all sections with Rachel. David was responsible for establishing printer parameters and producing the 3D-PAWS components and the commercial weather station. David was chiefly responsible for all 3D-PAWS sensor configuration and coding, as well as troubleshooting any issues encountered with the electrical systems. Also, David formatted multiple sections throughout the entire paper.
Chapter 1: Introduction
The University Center for Atmospheric Research (UCAR) and the National Center for Atmospheric Research (NCAR) began an initiative to produce a low-cost 3D printed surface weather monitoring station. The initiative, entitled 3D Printed Automatic Weather Station (3D-PAWS), was developed to expand observation networks in sparsely observed regions. The goals of the 3D-PAWS initiative are to build capacity to reduce weather-related risk in developing countries, observe and communicate weather and climate information to rural communities, and develop observation networks and applications to reduce weather-related risk.

Weather data monitoring has crucial importance to a wide range of economic, environmental, civil protection, and farming activities. Weather monitoring is also important for detecting changes in climate and providing data models that enable society to predict future changes in the environment. Weather forecast models can provide an accurate depiction of regional and local weather and climate patterns. The demand for these data, usually on an hourly or more frequent timescale, has increasingly been met by the development and widespread deployment of automatic weather stations (AWS) [1].

An AWS is an automated version of a conventional weather station and typically records data such as temperature, pressure, relative humidity, wind speed and direction, precipitation levels, and solar radiation. AWSs can be used to either save human labor or enable measurements in remote areas. Low-cost weather stations could be implemented in regions without previous access to localized weather data and be used to improve local forecasts and record global climate trends. Potential future applications include regional weather forecasting by assimilating data into regional weather prediction systems, such as the Weather Research and Forecasting Model; early alert and regional decision support systems that can provide real-time monitoring of precipitation that can inform flash flood guidance and other emergency support efforts; agricultural monitoring to support water resource management tools such as reservoir operation and generation of hydroelectric power; and health monitoring such as recording conditions that can lead to outbreaks of diseases like meningitis and malaria.

The goal of this project was to produce the 3D-PAWS system developed by UCAR and compare the system to a commercial weather station. UCAR’s 3D-PAWS initiative description suggests benefits of a 3D-PAWS system: low-cost, reliable micro-sensors; local assembly; and the potential to ‘re-print’ parts should the system fail. UCAR stated on their website that printing and assembly of 3D-PAWS would prove to be both more time- and cost-effective than using a commercial weather station. UCAR’s estimation was that a total 3D-PAWS installation could be completed in about one week.

This goal of project was to examine the time and cost associated with printing and assembling 3D-PAWS, the data collected by both 3D-PAWS and the commercial weather station, and the overall replicability of 3D-PAWS. The time and cost of printing and assembling 3D-PAWS was recorded to inform future replicability of UCAR’s product by other organizations. By comparing the data collected by 3D-PAWS and a typical commercial weather station, and the time and cost disparity of assembling and installing both stations, suggestions for changes to the 3D-PAWS project and potential use cases were identified.
Chapter 2: Background

The goal of this project was to investigate UCAR’s 3D-Printed Automatic Weather Station (3D-PAWS) as an alternative to commercial weather stations for collecting localized weather data. Through the assembly and installation of 3D-PAWS, the usability experience and reliability of using a non-standard weather station was compared to the use of commercially produced weather stations. 3D-PAWS has been implemented in regions with limited access to localized weather data and may be used to improve local forecasts that can further aid in predicting climate change patterns and agricultural and environmental practices.

This chapter outlines the current issues with access to weather data and the necessity and benefits of collecting localized weather data. An overview of weather and climate is provided, and the current problems of access to weather data are provided. The motivations of the 3D-PAWS project and possible solutions of using 3D-PAWS are discussed; and finally, preliminary research about 3D printing provided a technical background for use during assembly.

2.1 Weather, Climate, and Climate Change

The differences between weather and climate are the measure of time between events and the geographical scales they represent [2]. Weather is defined as the fluctuating state of the atmosphere, characterized by temperature, wind, precipitation, clouds, or other weather elements. Weather is the result of rapidly developing and decaying weather systems, and its predictability is limited. Discrete weather systems are unpredictable beyond one to two weeks [3]. Climate refers to the average weather in terms of the mean and its variability over a certain timespan and a certain area. Climate varies from place to place, depending on geographical factors such as latitude, distance to the sea, vegetation, presence or absence of mountains, etc.

Statistically significant variations of the mean state of the climate, typically persisting for decades or longer, are referred to as climate change [3]. As the climate changes, the probabilities of certain types of weather events are affected. As the earth’s average overall temperature has increased, weather phenomena such as heat waves, floods, and droughts have become more frequent and intense [3]. Projections of future climate change are shaped by fundamental changes in heat energy in the earth’s atmosphere. Increased, and more accurate, weather and climate monitoring are critical to documenting and predicting changes in the global climate.

2.2 Weather Variable Monitoring

The conventional knowledge of weather and climate focuses on those variables that affect daily life most directly: average, maximum, and minimum temperature, wind speed near the surface of the earth, precipitation, humidity, cloud type and cover, and solar radiation. Weather monitoring is important not just in defining climate, but also for detecting changes in climate and providing the data to input into models that enable better predictions of changes in the environment. Weather monitoring has developed an increased importance for a wide range of economic, environmental, civil protection, and farming activities [1]. Modern weather forecasting relies on computer-based models that take many atmospheric factors into account; these forecasts are made by collecting these quantitative data about the current state of the atmosphere at a given place.

The Global Climate Observing System (GCOS) has created a list of essential climate variables (ECVs). The atmospheric ECVs are: precipitation, pressure, surface radiation budget, surface wind speed and direction, temperature, and water vapor [4]. Some of the applications for meteorological data based
from these climate variables include: risk assessments, hydraulic structures design, crop water-use estimates, irrigation scheduling, input variables for climate change and hydrological models, and active and passive energy uses [5].

Precipitation, liquid or solid, is the “most important climate variable directly affecting humans” according to the WMO [4]. It’s duration, intensity, and frequency influences the water supply for personal consumption, use in agriculture, manufacturing, and power generation; and causes risk to life and the functioning of society when associated with floods, landslides, and droughts (hydrometeorological disasters) [4]. Precipitation is “closely related to cloud properties, a number of terrestrial ECVs, and to ocean-surface salinity. It is indicative of the release of latent heat within the energy cycle, as well as being at the heart of the hydrological cycle” [4]. Precipitation is typically measured using rain gauges, including a non-recording cylindrical container, float type, and tipping bucket type, which all measure the precipitation at a point [6].

Surface pressure is “a fundamental meteorological variable for which observations are required for initializing forecasts” [4]. Differences between surface pressure between stations provide information about the intensity of weather systems and indicate circulation patterns. Most atmospheric pressure sensors are based upon the use of an aneroid capsule, vibrating wire, or quartz crystal which provides an output in electrical analog or digital form [1].

The surface radiation budget is a balance between energy entering, reflected, absorbed, and emitted by the earth. Changing radiation balances cause changes in the temperature of the atmosphere that eventually affect the climate [7]. Sunshine and radiation are measured using sensors known as pyranometers that produce small, continuously variable voltages as a signal output. The output of these sensors, however, are vulnerable to electromagnetic interference on the signal cables, and also face problems with contamination on the front aperture. Deposits on uncleaned pyranometers have been shown to give a 2% loss in accuracy, making observation accuracy at unattended stations unreliable without regular cleanings [1].

Surface wind speed and direction influence the exchange of momentum, heat, moisture, and trace gas species between the atmosphere and underlying ocean and land. Surface wind is a driving force of ocean circulation that is responsible for global transport of heat and carbon, and it drives ocean waves, storm surges, and sea ice [4]. Surface winds directly influence sectors such as transportation, construction, energy production, human health, marine safety, and emergency management. Surface wind is also used to characterize the strength of tropical cyclones [4]. Wind speed is measured using conventional cup or propeller anemometers, and direction is measured using a potentiometer attached to a wind vane. Some wind vanes, however, employ a digital angle encoder [1].

Temperature impacts human lives, health, agriculture, and energy demands. Temperature is a key indicator of climate change, and its observations contribute to calculating the global-mean surface temperature [4]. Typical thermometers used in AWSs are pure metal resistance thermometers. It is recommended that radiation shields are used to protect the thermometer from effects of solar radiation, and optimally the shields should be artificially ventilated [1].

Water vapor content in the atmosphere, typically referred to as humidity, is the predominant gaseous source of opacity in the atmosphere, and accounts for approximately 60% of the natural greenhouse effect for clear skies [4]. Water vapor condenses to produce clouds, changing the atmosphere’s radiative properties and releasing latent heat that drives or modifies atmospheric circulation [4].
presence of water vapor also plays an important role in atmospheric chemistry [4]. Humidity sensors employ resistive and capacitive sensors that directly measure relative humidity. These sensors are relatively low-cost but are susceptible to poor performance in the presence of pollutants. The sensors also require corrections for measurements that occur below 0 °C (32 °F) or in saturated conditions (i.e., 100% humidity) [1].

Weather stations provide data about these ECVs that are used for weather forecasting and for studying weather and climate. Conventional weather stations house a rain gauge for liquid precipitation, barometer for measuring atmospheric pressure, pyranometer for solar radiation, anemometer for wind speed, wind vane for wind direction, thermometer for temperature, and a hygrometer for humidity.

The World Meteorological Organization (WMO) standardizes the instrumentation, observation practices, and timing of these observations worldwide[1]. The WMO guidelines specify siting and exposure, procedures of standardization, acceptable measurement techniques and procedures, and types of observation systems. The first edition of the Guide to Meteorological Instruments and Methods of Observation was published in 1954 and has been continuously reviewed to ensure that updates incorporate guidance material reflecting rapidly developing technologies. The guide is a “key resource that provides a description of most instruments, systems and techniques in regular use, from the simplest to the most complex and sophisticated” [1]. The current guide consists of 38 chapters detailing four major parts: measurement of meteorological variables, observing systems, space-based observations, and quality assurance and management of observing systems.

The WMO’s Guide to Meteorological Instruments and Methods of Organization provides siting and exposure guidelines that were developed from a study on published in 1993. In addition to sensor accuracy and reliability, meteorological observation should accurately represent the area of coverage. The representativeness of an observation is “the degree to which it accurately describes the value of the variable needed for a specific purpose” [1]. Different applications have preferred time and space scales, and the density of stations affects the resolution of phenomena.

### 2.3 Automatic Weather Stations

Before remote data acquisition technologies were available, monitoring weather conditions required someone to manually record values from a weather station. To improve coverage and reduce the manpower required for meteorological observations, a shift to automatic weather stations started to occur as remote sensing technologies became available. Instrument measurements are read out or received by a central data acquisition unit, and the data are processed locally at the AWS or at a central network processor [1]. An AWS is used to increase the number and reliability of surface observations by providing access to difficult to reach or inhospitable sites, supplying data outside of normal working hours, homogenizing weather networks by standardizing measurement techniques, lowering operational costs, and reducing human errors [1].

Because AWSs are controlled from long distances, the sensors used “must be robust, fairly maintenance-free and should have no intrinsic bias or uncertainty in the way in which they sample the variables to be measured” [1]. The sensors used are categorized as analog, digital, or ‘intelligent’. Analog sensors output a voltage, current, charge, resistance, or capacitance that is measured and translated into a meteorological measurement. Digital sensors collect signal outputs with information contained in a bit or group of bits, or signals that provide a pulse or frequency output. ‘Intelligent’
sensors perform data acquisition with microprocessor and processing functions that produce an output in serial digital or parallel form [1].

During the last two decades, the number of AWSs has greatly increased throughout the world. This rapid development has been a consequence of the need to provide meteorological data in near-real time [5]. For purposes of scientific resource management, meteorological data from automatic weather stations are typically recorded in large databases, but questionable results have been attributed to poor data quality because of non-existent or mixed quality control methods [5]. It is important to apply quality control procedures to meteorological data to ensure that meteorological information is properly generated and collected, to identify erroneous data to prevent misguided decision-making, and to solve problems for maintenance of the stations and periodic recalibration of sensors [5].

2.4 3D-PAWS Initiative

A network of weather stations is critical to making accurate regional forecasts and understanding long-term climate change, but in underrepresented regions of the world, fixing the broken or in-operational stations or installing new ones would require significant investment, training, and costly equipment [8]. To expand observation networks in sparsely-observed regions, the University Center for Atmospheric Research (UCAR) and the US National Weather Service International Activities Office (NWS IAO) have launched an initiative for 3D-Printed Automatic Weather Stations (3D-PAWS), which has the goals of: building capacity to reduce hydrometeorology-related risk in developing countries, observing and communicating weather and climate information to rural communities, and developing observation networks and applications to reduce weather-related risk [9]. 3D-PAWS can be used for many meteorological applications, including regional weather forecasting, early alert and regional decision support systems, agricultural monitoring, and health monitoring. System observations can be assimilated into regional models to improve mesoscale forecasts and real-time monitoring can give early warning of potential flooding [10]. The 3D-PAWS initiative brochure is provided in Appendix A.

The Joint Office of Science Support (JOSS), a program led by UCAR, focuses on filling in the “often substantial distances between high-tech weather stations in places like Africa” [8]. According to the African Ministerial Conference on Meteorology (AMCOMET) report, Africa has the least developed land-based observation network of all continents, having only 1/8th the minimum density suggested by the WMO. The AMCOMET report also attests that “accurate and timely weather forecasts and climate analyses and predictions will further improve human safety, prosperity, and livelihood and preserve precious natural resources to the benefit of communities, especially the most vulnerable”. The previous solution to this problem was installing high-end commercial weather stations. When these stations failed, however, parts could not be replaced due to units being discontinued by the manufacturers or lack of maintenance capabilities [8]. To remedy this problem, UCAR focused on designing a weather station that would be affordable and easy to fix utilizing 3D printing and cheap weather sensors.

The result of this initiative was 3D-PAWS, a “very high quality surface weather station [that] can be manufactured in about a week, at a cost of only $200-400, using readily available materials, microsensor technology, low-cost single board computers, and a 3D printer” [10]. The system operates using a Raspberry Pi single-board computer for data acquisition, processing, and communications. The onboard sensors are all low-cost sensors that can be easily replaced if they fail, and components of the station can be re-printed if they break [10]. While there is always the potential for individual sensors
to be discontinued by manufacturers, there are many options for sensors that could be implemented with 3D-PAWS.

The 3D-PAWS system is designed to measure pressure, temperature, relative humidity, wind speed, wind direction, precipitation, and visible/infrared/UV light. This is done using single-chip sensors, and the data is stored and transmitted using a Raspberry Pi 3 Model B. For 3D-PAWS all of the sensors use I²C or analog methods of communication and operate at +5V or +3.3V (as supplied by the Raspberry Pi). 3D-PAWS utilizes three Hall effect sensors, a pressure sensor, humidity sensor, temperature sensor, and radiation sensor. A summary of each sensor's specifications and usage is provided in Appendix B. The sensors specified for this project are commonly used and well documented but are not the only choice.

3D-PAWS was developed as an open source project, which gives users the tools and ability to modify their system to desired specifications. Additionally, if a meteorological service wishes to expand their station’s capabilities, new parts can be printed or additional sensors installed [10].

These sensors, when connected to the Raspberry Pi, provide the ability to record local weather data, store the data on the Raspberry Pi, and transmit it to an online web server. The web service used by 3D-PAWS is a community-led cyberinfrastructure initiative for the geosciences. Cloud-Hosted Realtime Data Services for the Geosciences (CHORDS) works in conjunction with Amazon Cloud Services to provide a web server and database. CHORDS can ingest and deliver data via http: requests using any software that is capable of issuing a request. The 3D-PAWS project uses Python-based code to collect and transmit data with the Raspberry Pi. The transmitted data can be displayed publicly on the CHORDS portal or be kept private and are displayed on a dashboard page. Further inspection of data from each individual sensor is available by a linked sensor page [11].

2.5 3D Printing

The microsensors used by the 3D-PAWS project require housings, or in the case of the anemometer and wind vane, movable components. Ideally, 3D printing would have the benefits of producing components locally and likely at a lower cost than purchasing one; and in the event that a component breaks it could be readily re-printed.

3D printing belongs to the family of manufacturing known as additive manufacturing (AM) and is the process of making an object by depositing material one layer at a time [12]. 3D printing can create objects out of polymers, metals, ceramics, and even concrete. 3D printing applications are currently limited to small-quantity production runs of small, complex items, including customized products, prototypes, replacement parts, and medical applications [13]. While 3D printers can print a broad range of materials, the most commonly used are polymers. For most 3D printers, the polymers are sold in the form of spooled filament with a diameter of either 1.75 mm or 1.85 mm. These filaments come in various colors and compositions to meet demands for different applications.

All 3D printers use computer-aided design (CAD) software to create thousands of cross-sections of the object being printed in order to determine how each layer is constructed [13]. These cross-sections are converted into a “standard tessellation language” (STL) file that is used to generate controls for the printer. The STL file that is exported from a CAD file is imported to a “slicer” software that generates layers (or slices) that translate to layers of deposited material on the 3D printer. Like a 2D inkjet printer, the nozzles in a 3D printer move back and forth while depositing a fluid. While 2D
printing is constrained to one plane, 3D printer nozzles move vertically to deposit multiple layers of material to cover the same surface [12].

3D-PAWS requires a polymer material that is highly UV resistant and doesn’t readily degrade when exposed to harsh outdoor conditions. The two most commonly used and readily available polymers for 3D printing are polylactic acid (PLA) and acrylonitrile butadine styrene (ABS), however neither are well suited to outdoor application. PLA biodegrades over time and has poor resistance to UV radiation. ABS is a sturdier plastic with a higher melting point and longer lifespan than PLA, but also wears under rough weather conditions and yellows under exposure to UV radiation [14].

To avoid plastic degradation from weather conditions, UCAR recommended that acrylonitrile styrene acrylate (ASA) be used for 3D-PAWS. ASA is weather and chemical resistant, which allows it to withstand harsh outdoor weather conditions. ASA has the lowest levels of yellowing among commonly used polymer filaments when exposed to UV radiation, and retains both its shape and color over time. It has similar strength and toughness properties to ABS plastic with the added benefit of UV resistance [14].

Different plastics require different print process settings when 3D printing. The parameters that most influence 3D printing are extruder temperature and bed temperature. A 3D printer’s extruder is a metal nozzle through which the plastic filament is thinly deposited onto a build surface [15]. The temperature of the extruder is dictated by the melting point of the plastic being used, and is typically specified by the filament manufacturer. The bed temperature is the temperature of the heated build platform and promotes adhesion and mitigates warping of prints. As with the extruder temperature, the bed temperature is typically specified by the filament producer.

The ambient temperature and rate at which a 3D printed object is cooled also have impacts on the quality of the final print. When the printed plastic is cooled there is contraction along the surfaces of the print, generating stress [16]. In cases where the layers are not cooled quickly enough, the plastic can widen out around the base of the print, what is sometimes referred to as an “elephant foot” [16]. Warping (both contraction and ‘oozing’) is best mitigated by using a heated bed and controlling the rate at which the print is cooled. Most printers incorporate a cooling fan that can be controlled and a variable temperature heated bed. Eliminating drafts by using a printer enclosure or printing in a room that has a steady ambient temperature can also prevent prints from being cooled too quickly [16].
Chapter 3: Methodology

With weather and climate monitoring being the primary motivation for the development of 3D-PAWS, its potential to provide access to data at a low-cost may be of interest to many different groups. The following methodology, developed from information gathered during background research, was designed to investigate 3D-PAWS as an alternative to conventional weather stations. 3D-PAWS is a promising alternative to high-priced commercial weather stations. The goal of this study was to assess the assembly and installation process of 3D-PAWS and examine the printing process, assembly, and reliability of 3D-PAWS as a weather station alternative. To do so, the following objectives were established:

1. Establish a technical and practical understanding of 3D printing methods.
2. 3D print, assemble, and install 3D-PAWS.
3. Determine a suitable location for installing 3D-PAWS and compare performance with a commercial weather station.
4. Perform a cost analysis of 3D-PAWS

Objective 1: Establish a technical and practical understanding of 3D printing

To meet objective one, it was necessary to establish technical knowledge of 3D printing techniques and methods before printing the 3D-PAWS components. Background research about 3D printing was conducted at the beginning of the project. To establish a technical and practical understanding of 3D printing, researched topics included the characteristics and applications of 3D printing, printer specifications and use, and filament types.

To establish a practical knowledge of 3D printing, trial prints were conducted with PolyLactic Acid (PLA) filament. PLA is useful in a broad range of printing applications, has properties that make it both odorless and low-warp, and prints at a relatively low extrusion temperature [17]. Rigid.ink, a filament supplier, recommends an extruder temperature between 180 °C (356 °F) and 210 °C (410 °F), a bed temperature between 20 °C (68 °F) and 45 °C (113 °F), and a bed primer of blue painter’s tape or glue stick. One of the first trial prints conducted with the PLA was an XYZ test cube (Figure 1).

![Image](image.jpg)

Figure 1: The first test print was a 20 mm (0.79 in) calibration cube with X, Y, and Z labeled faces. The STL file was obtained from thingverse.com.
Acrylonitrile Styrene Acrylate (ASA) filament was used during the printing process on the recommendation of UCAR. ASA filament was used for its durable properties, such as a high tensile strength and resistance to weather and chemicals, meaning it will withstand harsh outdoor weather conditions and would even demonstrate resilience against acid rain. ASA is UV resistant, which is a key property when choosing a suitable thermoplastic for outdoor settings.

To determine the proper print settings for ASA filament, a series of test-prints were performed varying different print parameters. Rigid.ink recommended an extruder temperature between 230 °C (446 °F) and 250°C (482 °F), a heated bed temperature between 90 °C (194 °F) and 110 °C (230 °F), and a bed primer of glue stick, a polyether imide (PEI) adhesive sheet, or blue painter’s tape.

The print test file was obtained from thingverse.com, an online repository of open source 3D printer files. The chosen test file was the same 20 mm (0.79 in) calibration cube with X, Y, and Z labeled faces used for the PLA test sample (Figure 2).

![ASA Trial XYZ Cube](image)

*Figure 2: ASA Trial XYZ Cube. Each cube took approximately 30 minutes to print and used 553 mm (1.81 ft) of filament. Visible surface defects are seen on the Z-face, and there is layer warping on the lower corner of the Y-face.*

The first four trials varied the temperature of the print bed and the extruder nozzles, while keeping the print speed constant (at the factory default setting of 3,600 mm/min (141.7 in/min)). The temperature of the print bed was set 5 °C (9 °F) higher for the first print layer to promote adhesion. The cooling fan was set to 0% power. Four temperature variation trials were conducted (Table 1).

<table>
<thead>
<tr>
<th>Temperature Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trial</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

*Table 1: Temperature variation trials and settings*
To test top and bottom finishing settings without using as much filament as the 20 mm test cube, a thin keychain object was obtained from thingverse.com and printed at different speeds and with different finishing options (Figure 3). With the chosen extruder temperature settings of 235 °C (445 °F) and bed temperature of 100 °C (212 °C), the keychain was printed four times with different settings (Table 2).

![Keychain Test Print](image)

**Figure 3:** This design was chosen because it had flat surface areas that would show the surface finishing, and also because the cut-out would demonstrate the quality of the print on internal edges.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Extruder Temperature (°C)</th>
<th>Bed Temperature (°C)</th>
<th>First Layer Bed Temperature (°C)</th>
<th>Speed (mm/min)</th>
<th>Layer Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>235</td>
<td>100</td>
<td>105</td>
<td>2400</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>235</td>
<td>100</td>
<td>105</td>
<td>6000</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>235</td>
<td>100</td>
<td>105</td>
<td>2600</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>100</td>
<td>105</td>
<td>2600</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2: Keychain Test Print Settings. The first test of the keychain was printed at a rate of 2400 mm/min (94.5 in/min) and the second at 6000 mm/min (236.2 in/min). For the third print, the rate was set at 2600 mm/min (102.4 in/min), and an additional two solid layers were printed on the top and bottom (for a total of four solid layers on the top and bottom).

The visually best results of the keychain test prints were used to determine the print speed that was used for printing the 3D-PAWS components.

**Objective 2: 3D printing and assembly of 3D-PAWS**

To meet objective two, the determined print parameters were used to generate the print code files, the files were organized, and the parts were then printed.

Before assembly of 3D-PAWS it was necessary to print all 127 components with ASA filament. The printing was done on a Flashforge Creator Pro 3D printer with the following print parameters:

- 2600 mm/min (102.36 in/min)
- 235 °C (455 °F) Extruder Temperature
- 100 °C (212 °C) Bed Temperature
- 50% infill (except for very small connector components that used 100%)
- 0.15 mm (0.006 in) layer thickness
- 4 solid base layers
- 4 solid top layers
- 5 raft layers with a top surface of 100% infill
- 10% support structure infill

2.1: Print File Separation and Organization
To facilitate printing, the STL files provided by UCAR were organized into folders by sensor or function. The ten separate groups correlate to the ten component groups of the 3D-PAWS system. The ten separate groups were the: anemometer, cables, frame, GPIO, Pi Tube, radiation sensor, radiation shield, radiation shield wiring, rain gauge, and wind vane.

These folders separated the large number of STL files into manageable groups sorted by station section. Each individual folder contained a PowerPoint assembly document with step-by-step instructions and computer-generated images for visual reference, and a folder labeled ‘Designs’. The ‘Designs’ folder contained all of the individual STL files of the components required for the weather station. STL files are the files output from a computer aided drafting (CAD) software that provides all of the construction data in a format that can be processed by 3D printing slicer software. The software, in this case Simplify3D, deconstructs the STL file into individual slices that correspond to the layers of filament that are deposited by the printer.

The copy of the files provided from UCAR was in one of its first iterations. As the 3D-PAWS system hadn’t yet been completely refined, there were cases where STL file names were not always clear or did not match the names in the assembly document. To prevent confusion during printing, the files were systematically renamed using the format of:

[Group][Part Name][Copies X]

The number of copies of each print was provided in the 3D-PAWS Assembly Instructions. For example, the anemometer cup file, of which there were three copies to print, was renamed to “Anemometer Cup 3X”.

The STL files were further sorted into print runs, groupings of parts that could all be printed on the same print bed. The limiting factor to the number of parts that could be printed in one run was determined by the print volume of the printer used for this project, a Flashforge Creator Pro, which was 22.5 cm x 14.5 cm x 15.0 cm (9 in. x 6 in. x 5.7 in.). To determine the parts that could be printed together, the STL files from each sensor group were imported into Simplify3D one by one until the print bed was full or nearly full. The “center and arrange” feature in Simplify3D evenly arranged the parts across the bed with even spacing between pieces. This sorting separated the components into 37 separate print run files.

2.2: Component Printer Supports and Rafts
It was noted during several initial print attempts that components would fail to print correctly due to lack of support for large overhangs, causing layers to cross, droop, or tear. To remedy this issue, Simplify3D offers a feature that will automatically generate support structures below components that
provide a stable printing surface away from the bed in the Z-direction. The support structures are printed simultaneously with the actual weather station component but with different print parameters (Figure 4).

Figure 4: Support material (in dark orange) automatically generated under the overhangs of the top leaf of the radiation shield.

The support material was expanded an additional 1 mm (0.039 in) past the perimeter of the part when automatically generated. For manually generated support structures, the resolution of the structure (i.e. the cross-sectional area of the pillar, default 4 mm (0.16 in)), and the placement determines the expansion past the perimeter. For easy separation from the printed part, the support material is offset from the part by 0.3 mm (0.012 in) (twice the thickness of the deposition layer) and was peeled off by hand once the part had cooled. In instances where the support was stuck to the part, the excess material was removed using a razor blade, a file, or sandpaper.

In addition to the support material generated for overhangs, a “raft” was used to secure the part to the bed. Initial print attempts failed due to inadequate adhesion to the print bed. To remedy this issue, rafts were generated under objects, which provided additional surface area in contact with the print bed, reducing the chance that a part would separate from the bed. Rafting generates five layers beneath the component being printed, with a completely solid top layer to which the component can adhere. The raft extends 2 mm (0.079 in) past the perimeter of the component (Figure 5).

Figure 5: Raft material generated below the cable components (arrow). The three additional layers of material with a larger surface area prevented the small cable components from separating from the print bed.
Once print runs had been separated, and the necessary support structures and rafts generated, the individual print runs were saved into a corresponding numbered folder as a .factory file. This file type is proprietary to Simplify3D, and saves print parameters, layout, and generated support structures in a single file. The .factory files that were originally generated with the print groups were modified to include the support material and exported as .x3g G-Code files to an SD card.

The exported G-Code files were named corresponding to the print run number and then content. For example, the anemometer cups were exported as “1 Anemometer Cups”. In instances where the printing process failed and required the revision of print parameters, the name was appended to designate that it was another trial, e.g. 1-2 Anemometer Cups.

2.3: Time Requirements of Printing Components
When generating the G-Code scripts to export to an SD card, Simplify3D provided an estimation of the time required for printing. This value was recorded in a spreadsheet to estimate the cumulative time required to print the 3D-PAWS. Upon the completion of print runs, the actual print time as reported by the FlashForge Creator Pro and the length of filament used were recorded for comparison to the estimated times.

A second spreadsheet was used to keep track of print failures and their cause. This spreadsheet also noted the amount of time required for reprints so a total printer run-time for the weather station could be calculated. Once printed, parts were stored in labeled, plastic zipper-closure bags, separated by original sensor or functional grouping. This organization was used to provide easier part management and help expedite assembly.

2.4: Recording Component Failures or Difficulties
3D printing does not always generate perfect objects on the first attempt, and may require modification of the print settings, bed adhesive, or bed leveling. To improve upon the printing and assembly files provided by UCAR, all print failures were documented (noted and photographed), and if possible, their cause of failure determined. If other components in the run were not affected it was only necessary to reprint the individual piece (or pieces). This was done by importing the failed component(s) into Simplify3D, generating new support structures if necessary, and exporting the revised G-Code file to the SD card.

Though initial printing parameters were established through the trial prints of cubes, modifications to the print settings were actively made throughout the printing process. Unsuccessful print runs lead to the development of pragmatic knowledge about print settings, which could be used to prevent failures in following runs.

It was not possible to print the rain gauge funnel on the FlashForge Creator Pro due to size limitations. To print this component an Ultimaker 2+ Extended 3D printer was used. Because the Ultimaker does not accept the same size filament as the FlashForge printer, the funnel was printed using black PLA.

The 3D-PAWS Assembly Documents were provided by UCAR as PowerPoint files. For convenience, all of these files were converted into PDFs, and compiled into a single file. The entire 400-page document was printed and spiral bound for reference during assembly. The benefit of having a hard copy of the document was that annotations could be made in the margins, and then the entire document was sent back to UCAR as a final deliverable.
As component groups were finished being printed they were assembled. This was not necessarily in the same order as presented in the assembly document, but each section was followed step-by-step. Each sensor component required assembly of the 3D printed parts, wiring and soldering, and attachment to the support frame. The approximate amount of time required for assembly of each sensor component was noted per when assembly started and ended.

All issues encountered during assembly were recorded in the margins of the assembly manual. These notations included minor changes, recommendations, or clarifications that would benefit a person assembling the station in the future. These issues are critical to the successful assembly of 3D-PAWS and require correction before mass distribution or publication.

**Objective 3: Weather Station Siting and Installation**

To meet objective three, installation sites were proposed and then assessed for suitability using weather station siting guidelines.

A number of sites in the Worcester, Massachusetts area were proposed as potential locations for siting weather stations. These suggestions were made on the basis that they were likely accessible and were presumed to have adequate exposure for the weather stations. The proposed sites had the initial requirement of being privately held to provide improved security of the weather stations. The selected sites were first ranked by suitability based on World Meteorological Organization (WMO) guidelines, and then by ease of access. The organizations or individuals responsible for the management of the selected properties were contacted to ask permission for use of their land. Due to site accessibility issues and limited internet connectivity at all four, the station was ultimately installed at Dr. Leslie Dodson’s house.

For siting, minimum requirements and desired requirements were proposed. The urban nature of Worcester prevented meeting all WMO guidelines, particularly distance from buildings or paved surfaces. Because the data collection aspect of this project was ultimately a comparative data study, less emphasis was placed on correct siting for WMO applications, as any data collection errors would be systematically reflected in both the 3D PAWS and the commercially available reference station. The WMO guidelines are outlined in the WMO’s publication *Instruments and Observing Methods: siting and Exposure of Meteorological Instruments* and the US EPA’s 2000 publication *Meteorological Monitoring Guidance for Regulatory Modeling Applications*. These two sources were condensed and summarized into parameters that would make for suitable siting locations.

The 3D-PAWS and commercial weather station were installed adjacent to each other. Because the stations were installed on private property and the ground was frozen at the time of installation, concrete-filled buckets with 7.5 ft (2.3 m) aluminum conduit tubes as support structures were used rather than dig and pour concrete footings in the ground. Two 80 lb (36.3 kg) bags of Quikrete were mixed per the manufacturer’s instructions and poured into 5 gal (0.02 m³) buckets. The posts were leveled using a 3-way post level and braced with wooden supports while the concrete cured.

The 3D-PAWS frame was assembled per the assembly instructions provided by UCAR using 1” (2.54 cm) diameter PVC pipe. Slight modifications to the frame were made in instances where particular PVC components could not be found in stores or to reduce the footprint of the station. In instances where modifications were made, they were recorded and documented for use in future recommendations.
The basic PVC frame of 3D-PAWS was assembled and attached to the aluminum support post in the laboratory before being transported to the installation location. The sensor components were attached to the frame once the base had been situated. An extension cable was run from an outdoor outlet to the 3D-PAWS station and a 120 V to 5 V USB adapter was used to power the Raspberry Pi.

The commercial weather station, an AccuRite Pro purchased from Amazon, required a wood surface to which it was possible to attach a supplied mounting bracket. Two U-bolts were used to secure a wooden plank to the aluminum post and the station was attached using the supplied wood screws. The commercial weather station was installed adjacent to the 3D-PAWS system, the two stations approximately 1.5 m (4.9 ft) apart (Figure 6).

![Figure 6: 3D-PAWS (left) installed next to the AccuRite commercial weather station (right)](image)

The proximity of the two stations allowed for direct comparison of data and observation. Within a 10 m$^3$ (353 ft$^3$) representative area it is assumed that the range of deviation for temperature is less than 0.1 °C (0.18 °F) [18]. Given this, it was assumed that all other weather metrics within the same spatial volume would be comparable.
3.1: Comparison of 3D-PAWS and Commercial Weather Station

The data collected by 3D-PAWS was recorded to the CHORDS portal that was established using an Amazon Web Services account. The sensor samples were posted to the portal using a request.get command in Python. The original code was provided by Paul Kucera at UCAR but was modified for this project. The modifications to the code were recorded and the Python files saved to a folder on the Raspberry Pi. The data ingested by the portal was downloadable in a comma-separated values (CSV) file format for analysis in a spreadsheet program. The CHORDS portal also provided data visualization services that displayed system uptime and number of sensor samples.

The data collected by the commercial weather station were not in an accessible format that could be downloaded to a computer or transmitted to a website. Weekly data (maximum and minimum temperature) were collected manually from the indoor display for comparison to the data collected from 3D-PAWS. To supplement the commercial weather station data, temperature, humidity, and pressure values were gathered from NOAA weather records.

In addition to data comparison, the two stations were visually inspected for differences in performance. The movement of the anemometer and wind vane were comparable in person by observation and was the only method of comparison for these sensors as the code for the anemometer and wind vane did not work for this installation of 3D-PAWS.

Objective 4: Cost Analysis

To meet objective four, the cost of 3D-PAWS was estimated before starting the project, and the expenses incurred during the project were compared to the initial estimate. The expense tracking for this installation was used to provide a recommendation for the expected total cost of 3D-PAWS and for comparison to the installation of a pre-built commercial weather station.

The 3D-PAWS assembly document provided a list of components that must be purchased for each component group. These items were compiled into an Excel spreadsheet with the quantity of each required. The price of each item was found on Amazon.com, homedepot.com, or Adafruit.com. If an item could not be found on one of these sites, a supplier was found using Google and listed. These prices were used to create an estimate for the total cost of building a 3D-PAWS system. A second parts list was created to keep track of the estimated and actual cost of each part. The Excel spreadsheet used to keep track of costs contained the estimated cost and actual cost of individual parts, including tax and shipping costs.

Within the assembly instructions, UCAR also specified the tools needed to complete the 3D-PAWS assembly. Many of the tools required to build this weather station were acquired from the WPI Civil and Environmental Engineering Department’s lab storeroom. Given that not every group looking to 3D print a weather station would have access to all of the tools listed, it was necessary to estimate the total cost of tools needed to complete this project. The price estimates were gathered from Amazon.com and recorded in a spreadsheet. Because 3D printers were readily available, it was possible to undertake this project without needing to purchase a 3D printer. Because the price of a 3D printer can vary greatly, the estimated cost was based on the printer model used to complete this project: the Flashforge Creator Pro. This did not include the cost of the Ultimaker 2+ Extended, but the fact that not every component can be produced on the Flashforge Creator Pro should be considered for the production of 3D-PAWS.
Chapter 4: Results and Discussion

The previously detailed methods were used to assess the assembly and installation of a 3D-PAWS system, examine the 3D printing process, and reliability of 3D-PAWS as an alternative to a commercial weather station. The results of the methods for establishing a technical understanding of 3D printing, printing and assembling 3D-PAWS, siting and installing the station, and performing a cost analysis are detailed in this chapter.

Objective 1: Establish a technical and practical knowledge of 3D printing

1.1: Determining Printer Settings

There were no specified print speeds or resolution from either UCAR or rigid.ink. Because these parameters were not known it was necessary to print several trials before choosing settings for the production of 3D-PAWS. To determine the parameters that produced high-quality prints, a series of test objects was printed on the Flashforge Creator Pro. As previously detailed in the methodology, the extruder and bed temperatures of the printer were varied while using ASA filament to print 20 mm (0.79 in) test cubes. The cubes were visually inspected, and the temperatures that produced the visually best results were used in later print settings (Figure 7).

![Figure 7: ASA Trial Print Cubes. Trials in order 1 to 4 from left to right. Visually best results were obtained with trial 4, which shows no visible warping or surface distortion between layers. The Z-surface of the cube exhibits some patchiness.](image)

The visually best results were produced by Trial 4 with an extruder temperature of 235 °C (455 °F) and a bed temperature of 100 °C (212 °F). Though the print layers appeared clean and even with little warping, the finishing on the top layers was discontinuous as seen in Figure 7, trial three.

Good surface finishing was assumed to be a function of printer temperature, but the test cubes revealed this to be untrue. To test the quality of top and bottom surfaces as a function of print speed, a flat keychain object was printed (in the interest of using less filament than a full cube) at varying speeds. As with the test cubes, the resulting prints were visually inspected for quality, and the best results were used for later print settings.

A reduced print speed of 2600 mm/min (102.4 in/min) gave much better results for the top finish layer. The print layer height was then reduced from 0.25 mm (0.01 in) to 0.17 mm (0.007 in) to 0.1 mm (0.004 in) to determine the change in print quality with respect to the change in layer thickness. Though 0.1 mm (0.004 in) provided the best print quality, the difference between 0.1 and 0.17 mm was almost indistinguishable. Because a thinner print layer requires more layers to be printed, thinner layers require more time to print. Ultimately, it was decided to use a layer thickness of 0.15 mm (0.006 in) at 2600 mm/min (102.4 in/min).
Objective 2: 3D Printing and Assembly of 3D-PAWS

After establishing a practical knowledge of the process of 3D printing, it was possible to print the components for 3D-PAWS. Using the print parameters determined in the previous section, the components created by UCAR were printed and assembled. The following section documents the printing and assembly process and the outcome of the final product.

2.1: Organizing Component Groups and Producing Print Files

Because the copy of files provided by UCAR was still in a draft phase, the naming system was not always clear, or did not exactly align with the assembly document. There were a total of ten component groups that required printing, with a total of 123 individual parts. The printer files were sorted into print runs, corresponding to groupings of parts that would fit on the print bed at the same time. This sorting created 37 individual G-code files to be printed.

2.1.1. Support of Overhangs

The first two attempts at printing the anemometer cups (the first print group) failed to adhere to the print bed. Further inspection of the STL computer model after importing to Simplify3D showed that there was a small gap between the print bed and the anemometer cup because of the geometry of the object (Figure 9).

Figure 8: Trial 3 produced the visually best surface finishing, however printing with a .1 mm (0.0039 in) layer resolution drastically increased print time. The surface finishing for trial 4 was determined to be adequate, but the layer resolution for printing 3D-PAWS was increased from 0.17 (0.0067 in) to 0.15 mm (0.0059 in).

Figure 9: Gap between the surface of the print bed and the anemometer cup.
During initial part printing, a number of print runs failed because they failed to adhere to the print bed, or overhangs drooped or fell apart (Figure 10).

Initially, the factory-default setting of support generation was used, which created support pillars with an infill of 40%. After several larger prints failed to print because of significant warping, it was realized that such dense infill caused uneven rates of cooling across the part and led to unwanted warping around the edges as they cooled more quickly than the center of the component (Figure 11).
Figure 11: Uneven cooling caused by a dense 40% infill resulted in warping and separation from the print bed. The support infill looks as though it is part of the object being printed, and in addition to causing warping, the 40% support was difficult to remove from the surface of the component.

This was remedied by reducing the infill percentage from 40% to 10%, which generated adequate support, while allowing for even airflow around the component. After this parameter was modified there were no printing failures due to warping.

During several early print groups that failed, it was noted that both smaller and larger prints would separate from the bed because of an insufficiently large surface area for adhesion to the bed (Figure 12).

Figure 12: Components separating from the print bed. Even with a reduced infill, there were still issues with prints separating from the bed. This was more noticeable on prints that took up a larger space on the print bed, and it was assumed that this was due to uneven heating of the print surface.

This problem was remedied by generating a raft around the bottom of the part that provides five layers beneath the part with a solid top layer to which the component could adhere. Addition of the raft greatly reduced the number of failures caused by parts separating from the print bed.

2.2: Printer Run Time
Simplify3D provided an estimated printer runtime when the print files were exported to the SD card. The estimated print times were recorded and compared to the time actually required (as reported by the printer) (Table 3).
<table>
<thead>
<tr>
<th>Name</th>
<th>Parts</th>
<th>Estimated print time (h)</th>
<th>Actual print time (h)</th>
<th>Added print time (h)</th>
<th>Filament used (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anemometer Cups</td>
<td>3</td>
<td>2.60</td>
<td>2.80</td>
<td>-</td>
<td>5.8954</td>
</tr>
<tr>
<td>Anemometer Body</td>
<td>7</td>
<td>5.52</td>
<td>5.85</td>
<td>3.88</td>
<td>13.217</td>
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<tr>
<td>Cable Connectors</td>
<td>22</td>
<td>4.28</td>
<td>4.72</td>
<td>-</td>
<td>10.198</td>
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<td>Frame Elements</td>
<td>6</td>
<td>10.03</td>
<td>10.62</td>
<td>-</td>
<td>30.266</td>
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<tr>
<td>GPIO Elements</td>
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<td>5.78</td>
<td>6.58</td>
<td>-</td>
<td>14.059</td>
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<tr>
<td>RPI End Cap</td>
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<td>4.72</td>
<td>4.72</td>
<td>5.78</td>
<td>12.727</td>
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<tr>
<td>RPI Threaded Securing Band</td>
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<td>3.30</td>
<td>3.43</td>
<td>-</td>
<td>9.1663</td>
</tr>
<tr>
<td>RPI Securing Band</td>
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<td>3.02</td>
<td>3.37</td>
<td>-</td>
<td>8.7595</td>
</tr>
<tr>
<td>RPI Bolts</td>
<td>6</td>
<td>2.38</td>
<td>3.10</td>
<td>-</td>
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<tr>
<td>RPI Tube Support</td>
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<td>8.78</td>
<td>9.40</td>
<td>-</td>
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<tr>
<td>Radiation Sensor</td>
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<td>3.82</td>
<td>4.23</td>
<td>-</td>
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<tr>
<td>Radiation Shield Base</td>
<td>2</td>
<td>8.82</td>
<td>9.48</td>
<td>7.60</td>
<td>24.729</td>
</tr>
<tr>
<td>Radiation Shield Base Plate</td>
<td>1</td>
<td>2.62</td>
<td>2.83</td>
<td>-</td>
<td>7.9506</td>
</tr>
<tr>
<td>Radiation Shield Fasteners</td>
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<td>4.53</td>
<td>4.95</td>
<td>-</td>
<td>13.42</td>
</tr>
<tr>
<td>Radiation Shield Center Screen</td>
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<td>2.12</td>
<td>2.45</td>
<td>2.77</td>
<td>6.138</td>
</tr>
<tr>
<td>Radiation Shield Middle Leaf</td>
<td>1</td>
<td>10.07</td>
<td>10.82</td>
<td>-</td>
<td>28.547</td>
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<tr>
<td>Radiation Shield Middle Leaf</td>
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<td>10.83</td>
<td>-</td>
<td>28.547</td>
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<tr>
<td>Radiation Shield Middle Leaf</td>
<td>1</td>
<td>10.07</td>
<td>11.05</td>
<td>-</td>
<td>29.566</td>
</tr>
<tr>
<td>Radiation Shield Middle Leaf</td>
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<td>10.07</td>
<td>11.12</td>
<td>-</td>
<td>29.566</td>
</tr>
<tr>
<td>Radiation Shield Middle Leaf</td>
<td>1</td>
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<td>11.12</td>
<td>-</td>
<td>29.566</td>
</tr>
<tr>
<td>Radiation Shield Next to Top Leaf</td>
<td>1</td>
<td>13.48</td>
<td>14.28</td>
<td>-</td>
<td>41.393</td>
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<tr>
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<td>2.63</td>
<td>3.15</td>
<td>6.22</td>
<td>7.3883</td>
</tr>
<tr>
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<td>2.63</td>
<td>3.15</td>
<td>-</td>
<td>7.3883</td>
</tr>
<tr>
<td>Radiation Shield Screen Ring</td>
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<td>2.63</td>
<td>3.15</td>
<td>-</td>
<td>7.3883</td>
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<td>Radiation Shield Screen Ring</td>
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<td>2.63</td>
<td>3.15</td>
<td>-</td>
<td>7.3883</td>
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<tr>
<td>Radiation Shield Shaft</td>
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<td>1.48</td>
<td>1.75</td>
<td>-</td>
<td>4.6207</td>
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<tr>
<td>Radiation Shield Base</td>
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<td>7.15</td>
<td>9.58</td>
<td>-</td>
<td>26.088</td>
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<tr>
<td>Radiation Shield Top Leaf</td>
<td>1</td>
<td>11.82</td>
<td>12.57</td>
<td>-</td>
<td>36.295</td>
</tr>
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<td>Radiation Shield Wiring Harness</td>
<td>9</td>
<td>4.38</td>
<td>5.02</td>
<td>-</td>
<td>10.512</td>
</tr>
<tr>
<td>Rain Gauge Cover</td>
<td>1</td>
<td>11.03</td>
<td>11.67</td>
<td>5.02</td>
<td>31.075</td>
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<tr>
<td>Rain Gauge Base</td>
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<td>8.53</td>
<td>8.98</td>
<td>-</td>
<td>22.935</td>
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<tr>
<td>Rain Gauge Funnel</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rain Gauge Funnel Rim</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rain Gauge Inner Cover</td>
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<td>8.88</td>
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<td>11.10</td>
<td>-</td>
<td>26.583</td>
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<td>Wind Vane Base</td>
<td>2</td>
<td>3.30</td>
<td>3.77</td>
<td>-</td>
<td>9.635</td>
</tr>
<tr>
<td>Total</td>
<td>123</td>
<td>221.43</td>
<td>242.05</td>
<td>31.27</td>
<td>628.22</td>
</tr>
</tbody>
</table>

Table 3: Printing time and filament used

The overall estimated printer runtime to complete all 123 parts was 221.43 hours. The total amount of printer runtime for re-printing parts that did not successfully print the first time was 31.27 hours. The total printer runtime to completely print the 3D-PAWS components was 273.32 hours.
Given that it required 273.32 hours of printer runtime to print the 3D-PAWS system, it seems unlikely that an entire station could be printed and assembled in one week as suggested by the UCAR website. If the printer had been continuously run, it would have required just over 10 days to print the components. Given the physical constraints of the 3D printer's bed, and limitations to how quickly ASA plastic can be printed, there are no possible print settings that could be modified to decrease the amount of time spent printing; and modifying print settings would have had negative impacts on the final quality of the printed components.

It is unclear how UCAR developed the recommendation that 3D-PAWS could be printed and assembled in one week. Printing all 123 parts of 3D-PAWS took five weeks, and the assembly three. In total it required eight weeks of printing and assembling the 3D-PAWS, which is significantly longer than the advertised timeframe of “about a week” [10].

2.3: Printing and Assembly Issues
3D printing does not always give desired results on the first try. Issues such as improper bed adhesion, insufficient support material, extruder malfunctions, glitches in the code, or a poorly leveled bed can cause the printing of a part to fail. Additionally, there were also prints that failed because of their design or orientation on the bed and lack of necessary support. To improve upon the printing and assembly files provided by UCAR, all print failures were noted and photographed, and if possible, their cause of failure determined. The analysis of failures throughout the printing process provided suggestions for modifications that may be beneficial to the 3D-PAWS program.

In addition to problems encountered with 3D printing components, there were problems encountered during assembly of 3D-PAWS. The most commonly encountered problems were tolerance issues when fitting parts together and imperfections in the surfaces of printed parts. There were also assembly steps in the UCAR documentation that were confusing or missing. The problems encountered during the assembly are described in the following sections by component grouping.

2.3.1: Anemometer Printing and Assembly
The printing process of the anemometer assembly was primarily hindered by the lack of support on the print bed. The anemometer cups, if not printed with support material, do not touch the surface of the print bed because of its geometry, as previously shown in Figure 9. As the end that connects to the hub is the tallest part of the component, the cone of the cup itself does not touch the bed. The complete assembly of the anemometer is shown in Figure 13 for later reference to components.
The first problem encountered with the anemometer assembly was the thickness of the anemometer shaft (component 5). As printed, the diameter of the shaft was too large to fit through the bearing or fit into the anemometer hub (component 2). This required sanding the shaft with 200-grit sandpaper and filing down the inside of the anemometer hub. This was not a major issue and was easily resolved, but the diameter of the shaft should be reduced in the CAD model for easier assembly.

There were slight tolerance issues encountered with the anemometer cups being attached into the hub (component 2), but this was mostly caused by small defects on the surfaces of the components. This issue was resolved by lightly sanding the components with 400-grit sandpaper to smooth out surfaces before joining. There is no change to the CAD model that could prevent this problem.

Addition of the support structures and raft rectified all printing issues encountered with the anemometer sensor assembly. The sensor body did have to be re-printed because the lower wall snapped off during assembly (Figure 14). This was no fault of the design, but of too much pressure being applied while trying to remove infill material.
The assembly documents do not specify the size of the magnet (component 6) required to trigger the Hall effect sensor. This required measuring the mounting holes after printing the anemometer shafts and ordering the correct magnets. The measured hole for the magnet was 3.2 mm (.125 inches) in diameter with a thickness of 1.6 mm (0.0625 inches).

The anemometer component that was most difficult to use during assembly was the soldering jig. The 3D printed soldering jig was intended to make assembly and soldering of the sensor circuitry easier but had several issues that made it difficult to use. The first issue encountered was that the resistors and capacitors ordered did not have the same physical dimensions as the ones used by the UCAR developers. The capacitors purchased for this circuitry had legs that were too short to meet the Honeywell bi-polar Hall-effect sensor, and required soldering on an additional length of wire taken from an extra resistor (Figure 15).

Soldering within the jig was also difficult. Because of its shape and how the wires were seated in the plastic channels, it was difficult to solder the wires together without melting the jig with the tip of the soldering iron. The molten solder also melted into the plastic making it difficult to remove the components from the jig. Without melting the plastic, it was nearly impossible to get the wires hot

---

Figure 14: Base of anemometer snapped off during assembly

Figure 15: The legs of the capacitor did not meet the legs of the Hall-effect sensor.
enough to adequately solder them together. They could be tacked into place but had to be re-soldered once removed from the jig.

When assembling the wire attachments with the DuPont 2.54 mm pitch crimp connectors, the casing plus the solder required on the components was too large to fit within the 3D-printed sensor casing (Figure 16).

![Image of crimp connector](image1.png)

*Figure 16: Crimp connector casings and solder do not fit within the casing, causing bowing at the middle of the assembly.*

Fixing this tolerance issue required sanding down the back of the sensor housing and sanding down the front of the crimp connectors. A looser tolerance or a slightly larger casing would have avoided this issue. A solution to this issue was removing the crimp connectors and instead soldering directly to the wires (Figure 17).

![Image of soldered components](image2.png)

*Figure 17: Components soldered together without using the soldering jig or DuPont crimp connectors. The tolerance between the cover and the components was still tight and still required some sanding, though less than with the crimp connectors. The soldered components are shown here tacked into place with hot glue before the cover was added.*
In the sensor assembly documentation, the diagram orientation made it difficult to follow along with wiring and soldering (Figure 18). Instead of being oriented as the reader would look at the component in front of them, the diagram was oriented nearly 180° away from the reader so all assembly took place opposite of how it was laid out. The lack of an official schematic also made the assembly process more difficult. Though some audiences will benefit from a visual, step-by-step representation of assembly, a wiring schematic would eliminate any confusion caused by the orientation of the diagrams and similarity of colors. The step-by-step instructions were used to draw and design a wiring schematic (Figure 19).

![Figure 18: The orientation of the assembly examples made it difficult to follow along. The legs of the capacitor and resistor are hard to discern because of the all-yellow coloring scheme, and in the first image it is not clear into which slots the capacitor legs are being placed.](image)

![Figure 19: Wiring schematic of the Hall-effect sensor in the anemometer assembly](image)

### 2.3.2: Cable Connector Printing and Assembly

The cable components were initially printed using the software-default support infill of 40%, however it was difficult to remove the support material from the narrow threading (Figure 20). Resolving the issue of support material inside of the component threads required reducing support infill to 15% and using a thin file to scrape out excess material.
2.3.3: GPIO Harness Printing and Assembly

As noted in the printing cable components section, the 40% support infill was too dense for small components. The support infill was again reduced to 15% to prevent the same problems as were encountered with the cable components. Because the GPIO harness components were small and had thin walls, the infill of the parts themselves was increased to 100% to provide additional strength.

The GPIO harness was the most time-intensive component to assemble. The lack of a wiring schematic made it difficult to follow along and organize wires. There was no standard organization, and the attachment points of cables was not always clear. The wiring was organized by color, but not by component. This organization required frequent cross-references between sections and pages to determine where components were to be connected.

The step-by-step figures should also include a final picture of the complete wiring harness from several orientations. The figures as they were had an orientation that made it difficult to discern between wires, and in some figures, the wires were changed from their original color to yellow (Figure 21).
Figure 21: Example images taken from the UCAR assembly documentation for the GPIO harness. The images in this section are unclear because of how close together the wires are. Because none of the wires are labeled, or require cross-referencing between several sections, it is hard to follow these assembly instructions.

It seems this was done to isolate other wiring organizations, but it made it more difficult to check that all wires were in their correct positions. Following each step and frequently cross-referencing between them allowed for the assembly of the wiring harness. To make future assemblies clearer and more organized, the entire 3D-PAWS system was put together on a breadboard in a clearly laid out in organized manner (Figure 22).
Figure 22: All weather station sensors and connections on a breadboard.
The bread-boarded circuit was used to consolidate all of the connections into one image and made the assembly instructions clearer and easier to follow. Instead of using instructions that follow wires by color, it would be easier to check correct wiring configuration if the connected component for each wire was listed. The completed wiring harness was disorganized and had a tendency to get tangled. To contain the wires in a more manageable way, they were taped together using electrical tape (Figure 23).

![Completed GPIO harness](image)

Figure 23: Completed GPIO harness

The assembly of common rails in the GPIO harness seemed to be an extraneous step that required printing of eight additional components, adding nearly two hours of printing time, and took a significant amount of time to assemble. The common rails provide connections to 3.3V, ground, Serial Data Line (SDL), and Serial Clock Line (SCL). The common rail is an efficient method for wiring connections, however the 3D printed assemblies and soldering required could have been eliminated.

A common rail is simply a point where multiple wires are joined as their connections all have the same input or output. The simplest way of creating a common rail for 3D-PAWS would have been soldering together the four or five wires required at each joint, and then covering them with electrical tape or hot glue. This would have eliminated the necessity of soldering together header pins and would have served to reduce the overall size of the wiring harness.

2.3.4: Pi Tube Printing and Assembly

The Pi Tube houses the wiring harness and Raspberry Pi in a water-resistant container, shown in Figure 24.
The Pi Tube components were the first large components printed - they took up most of the print bed and had to be printed individually. Because the parts were so large, there were issues with bed adhesion and warping (Figure 25).

Figure 25: The base of the Pi Tube separated from the print bed on the front screw joint. It is likely this separation was due to an uneven temperature profile on the print bed caused by the difficulty of maintaining an evenly heated surface using electronic controls. The warping of large, flat parts was mitigated by increasing the bed temperature to 105˚ for the first 10 layers and increasing the extension of the raft around the part.

The first trial of the pi tube end cap failed completely due to an incorrectly leveled bed. It is likely that the bed became un-leveled over time through regular printer use (Figure 26).

Figure 26: The right edge of the base plate appears much thinner than the left and there was evidence of the printer nozzle touching the bed. It is likely that the offset of the base from the top ring was caused when the nozzle caught the edge of the base, sliding it across the bed. Re-leveling the bed fixed this issue.

The bed was re-leveled using the Flashforge leveling software that was included with the printer, which fixed the issue of thin base layers and filament not correctly adhering.

The final attempt at printing the Pi tube end cap had a slight warping defect on one of the bolt holes, but this did not cause any problems with assembly. In the interest of saving filament, the part was not re-printed and did not affect assembly (Figure 27).
2.3.5: Radiation Shield Printing and Assembly
The radiation shield assembly protects the temperature, pressure, and humidity sensors from solar radiation for more accurate readings (Figure 28).
The radiation shield is the component group that required the longest time to print, taking 117.27 hours of printer runtime. The radiation shield leaves proved to be the most difficult components for which to determine the correct printer settings. The first print attempts warped and separated from the print bed because of inadequate adhesion and improper cooling (Figure 29).

![Image](image_url)

**Figure 29:** Separation from print bed and warping of the top leaf of the radiation shield. The warping was rectified by reducing the support infill to 10%, allowing the component to cool at a more even rate.

The large and dense components would cool faster at the thin edges than in the center, causing the edges to contract and separate from the bed. This was rectified by reducing the support infill to 10%. The less-dense support structures allowed the leaves to cool at a more uniform rate and prevented warping and bed separation.

The screen rings for the radiation shield could not be printed as provided. The squares of the screen physically did not touch, even with 100% infill settings applied. Printing the screen rings so they would not fall apart took five attempts to determine process settings and modifications to the STL file that would successfully produce a screen ring (Table 4 & Figure 30).

<table>
<thead>
<tr>
<th>Attempt</th>
<th>Process</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Increase infill percentage to 100%</td>
<td>Fail</td>
</tr>
<tr>
<td>2</td>
<td>Duplicate ring once</td>
<td>Fail</td>
</tr>
<tr>
<td></td>
<td>Center both on the Z-axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotate one ring 45˚ on Z-axis</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Duplicate ring once</td>
<td>Fail</td>
</tr>
<tr>
<td></td>
<td>Center both on the Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radially scale second ring by 2mm</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Duplicate ring five times</td>
<td>Successful, but screen holes were too small.</td>
</tr>
<tr>
<td></td>
<td>Center all on Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scale one radially by 1 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scale one radially by 2mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotate one by -1˚ on Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotate one by 1˚ on Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20% expansion of infill material</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Duplicate ring three times</td>
<td>Success</td>
</tr>
<tr>
<td></td>
<td>Center all on Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotate one by -1˚ on Z-Axis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotate one by 1˚ on Z-Axis</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4: Process settings and trials for repairing the center screen. The fifth print setting was chosen as the process to be used for all four screen rings and the center screen.*
Figure 30: Center screen squares with no physical connections (left) Most of the squares separated while removing the component from its raft. The same problem occurred with the larger screen rings. The screen ring on the right shows the modified printer file with connected squares.

As with the GPIO harness, the radiation shield assembly section would benefit from the inclusion of a wiring schematic. The radiation shield wiring harness was bread-boarded and used to create a wiring schematic (Figure 31).

Figure 31: Radiation shield wiring harness. Pins on RAD block: (1) +3.3V (2) GND (3) SCL (4) SDA
The GPIO harness included a 4-pin setting tool for inserting the common rails into their holders, but there was no setting tool for the 3-pin common rails that were required by the radiation shield wiring harness. To set the rails required shaving down the side of the 4-pin connector until it fit into the 3-pin holders. Because the rail holder was designed to have a very tight fit it was impossible to insert the pins without a setting tool. Any attempts to do so caused broken pins or pins slipping through the plastic header rail.

The inclusion of common rails, as with the GPIO wiring harness, seemed somewhat unnecessary and assembly could have been simplified by soldering the wires together and sealing with tape or glue. The common rails used in the radiation shield wiring harness were also slightly too large to fit through the spokes of the leaves in the radiation shield as one group and were difficult to pull through as specified. Without the large common rails, this assembly would have been much simpler.

### 2.3.6: Sensors
The 3D printed soldering jig was not printed because it was not needed to solder the components. In the event a person assembling a 3D-PAWS system had no experience with through-hole soldering, it may make sense to print the soldering jig, but through hole soldering can be accomplished quickly and easily using only a breadboard as a support. There were no issues encountered during the soldering of the sensors.

### 2.3.7: Rain Gauge Printing and Assembly
The rain gauge assembly uses a tipping counter mechanism to measure the volume of water collected during precipitation events. A funnel of a specified diameter collects the rainwater to determine how many inches of rain were collected (Figure 32).

![Figure 32: Rain gauge assembly diagram with numbered components for reference.](image-url)
The most significant issue encountered was the inability to print the rain gauge funnel (component 16) on the Flashforge Creator Pro that was used to print all of the other components. The size of the funnel was larger than the print bed (Figure 33).

![Figure 33: The digital rendering from Simplify3D of the rain gauge funnel extending past the edge of the print bed.](image)

This component had to be printed on another printer, the Ultimaker 2+ Extended, which was large enough to accommodate the extreme build volume. The Ultimaker printer only accepts a larger diameter (2.85 mm) filament, which was not available from the supplier, rigid.ink, at the time of printing. The funnel was printed out of black PLA filament as it was readily available and did not need to be ordered. The PLA rain gauge should be replaced with an ASA one once the filament is available (Figure 34).

![Figure 34: Temporary PLA funnel attached to rain gauge assembly at installation site.](image)
A similar issue was encountered with the rain gauge funnel rim (component 1). In the “Calibrating the Rain Gauge” section of the 3D-PAWS assembly instructions, it is necessary to calculate the diameter of the funnel rim to provide the correct surface area for measuring rain collected. After calculating the diameter, the CAD file must be modified with an open-source software called OpenSCAD and converted to an STL file for printing. It is unclear why modifying the CAD model was the method used for calibrating the rain gauge, when the code could have been modified to accept the provided diameter.

Assembling the rain gauge required producing the same Hall-effect sensor as the anemometer assembly, and the same issues were encountered. As with the anemometer’s sensor, this was rectified by removing the casings from the wires and soldering directly to the components (not using the soldering jig). When the sensor was inserted into the holder, there was some looseness noted, and a drop of hot glue was used to secure it in place.

The bucket stops (component 8) were included to determine the volume of water that produces a tip of the tipping bucket. In the assembly instructions there were three sizes of bucket stops references, however only one STL file was included.

When placing the tipping bucket assembly on the supports, the rivets would frequently slip off of the V-shaped support. A cap on the top of the support would have prevented the bucket from slipping off, especially when the sensor is being transported.

As with the anemometer, the size of the magnet required for actuating the Hall-effect sensor was not specified. It was the same size as the anemometer’s magnets, so it did not require ordering other sizes. Because the sensor did not work with the Raspberry Pi or software provided, the calibration steps were never completed, nor were the rain gauge screen or funnel rim assembled. These two components, as with the funnel, did not fit on the FlashForge Creator Pro used to print the rest of the 3D-PAWS system.

2.3.8: Wind Vane
This assembly measures wind direction using a rotary sensor and rotating wind vane (Figure 35).
The first attempt at printing the wind vane components failed completely due to a printer malfunction. It is unclear if the malfunction was due to improper bed leveling, or a clog in the extruder (Figure 36). The bed was re-leveled, and the nozzle cleaned with isopropyl alcohol. The subsequent print runs printed correctly without deformation.

Figure 36: Malfunction of the 3D printer caused failure of the wind vane components. The print bed became unleveled over time as a result of heavy use. The uneven surface caused the printer nozzle to collide with the print bed, resulting in smearing of the plastic material (as indicated by the orange arrow), or separation from the print bed (as indicated by the green arrow).

The wind vane shaft (component 4) required sanding to fit through the bearing (component 10) and into the wind vane (component 1). Aside from this there were no further problems with assembling the wind vane.

2.3.9: Frame Assembly
There were no problems encountered with printing the frame components, however when assembly started it was noticed that there were several missing parts. The parts list within the “Building the Weather Station” documentation did not list the correct number of swivel joints or leveling joints to print. The total number of swivel joints and leveling joints had to be counted directly from the assembly document and printed after it was assumed all of the parts had been completed.

As the frame could not be cemented into the ground, per the UCAR assembly instructions, the support posts were cemented into 5-gallon buckets as previously described in the methodology section. The assembly of the frame was straightforward as it only required the connection of the PVC pipes and super gluing the swivel and leveling joints to the connectors. All of the sensors were assembled and attached to the frame, but the only cable run was for the radiation sensor assembly. It was not possible to get the software for the other sensor to record data, and it was deemed unnecessary to run cables for in-operational sensors.

There were also PVC joints that could not be found in local stores, and it was necessary to make modifications to the frame assembly instructions. Both the rain gauge and Pi Tube assemblies required
modification to their frame attachments because the specified joints could not be found (Figures 37, 38).

Figure 37: The original assembly specifications of the rain gauge support are shown on the left. The top 4-way tee with a 90° side angle could not be found and was replaced with a standard 4-way tee and two 45° angled couplings as shown on the right.

Figure 38: The Pi Tube assembly required the same PVC joint that could not be found for the rain gauge. This was rectified by using a standard 4-way tee. The Pi Tube was also rotated vertically by 90° to reduce the overall footprint of 3D-P-AWS. With the assembly as specified, the Pi Tube protruded significantly from the frame. The original assembly instructions are shown on the left, compared to the modified assembly on the right.
Objective 3: Weather Station Siting and Installation

After completing the printing and assembly of the 3D-PAWS system, a site for installation was determined, and the station was installed adjacent to a commercial weather station for comparison.

3.1: Weather Station Siting

The WMO produced *Instruments and Observing Methods: Siting and Exposure of Meteorological Instruments* in 1993 as a guideline for placing weather stations. The United States Environmental Protection Agency used these guidelines to formulate the 2000 publication *Meteorological Monitoring Guidance for Regulatory Modeling Applications*. The combination of these sources provides clear recommendations for where weather stations should be placed to be most representative of the region they are surveying.

Weather stations typically have three sensor component groups: wind speed and direction, temperature and humidity, and precipitation. Each of these three sensor groups require similar siting requirements and were presented separately in both the EPA and WMO documents previously mentioned. The requirements of each sensor group are outlined in the three corresponding paragraphs below:

The anemometer and wind vane should be installed 10 m (32.81 ft.) above the ground, with sufficient distance from any obstacles or wind breaks. For an isolated tree or building, the distance to the sensors should be greater than ten times the height of the obstruction; for cities and forests, the distance to the nearest obstacle should be greater than twenty times the height of the obstruction. The optimal placement for an anemometer and wind vane would be in the center of a 200 m (656 ft.) clearing [18].

The temperature and humidity sensors should be located 2 m (6.56 ft.) above grass-covered ground and employ a standard shading apparatus to prevent exposure to direct sunlight [18]. The sensors should be located over an open, level area at least 9 m (29.5 ft.) in diameter, and protected from thermal radiation from the earth, sun, sky, and surrounding objects [19].

The rain gauge should be sited on level ground with the mouth horizontal and open to the sky. The height of the opening should be a minimum of 30 cm (1 ft.) above the ground, but higher if necessary to avoid splashing from the ground. Because precipitation gauges are sensitive to wind speeds, an effort to minimize the wind speed at the mouth of the opening should be made - either by a natural or constructed windbreak [19].

Most importantly, the weather station should be representative of the region for which it is intended to collect data. For a weather station to be representative of its region, no unusual values must be found for any parameters being measured [18]. Generally speaking, it is recommended to site stations in regions with simple topography with no surrounding obstacles or irregularities.

Because there are so few locations in the urban area of Worcester that would satisfy all of the World Meteorological Organization’s recommendations for weather station siting, concessions had to be made. Since this study’s intention was data comparison and ease-of-use analysis of 3D-PAWS, the representativeness of the weather station to the region is less important. Any irregularities in meteorological conditions will affect both the 3D-PAWS system and the commercial weather station that are to be compared, so any errors will be systematic, and still comparable.
Beginning the project, there were four suggested locations at which we could potentially install the two weather stations: the Worcester Regional Airport, WPI President Laurie Leshin’s house, Dr. Sakulich’s house, and the roof of Salisbury Laboratories on the WPI campus. The proposed sites were ranked by how well they met WMO siting guidelines, and pros and cons of each site were determined (Table 5).

<table>
<thead>
<tr>
<th>Weather Station Location Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>Worcester Regional Airport</td>
</tr>
<tr>
<td>Pros</td>
</tr>
<tr>
<td>Large, flat, open-space with grass</td>
</tr>
<tr>
<td>Ability to compare data to airport weather station</td>
</tr>
<tr>
<td>Close to Campus</td>
</tr>
<tr>
<td>Internet connectivity</td>
</tr>
<tr>
<td>Close to station on Weather Underground network for data comparison</td>
</tr>
</tbody>
</table>

Table 5: Site Rankings

Because of accessibility issues with the Worcester Airport and President Leshin’s house, and poor internet accessibility at Dr. Sakulich’s house, it was decided to use Dr. Leslie Dodson’s house as the location for placing the weather stations although not previously analyzed. Though her house did not provide optimal conditions for collecting data representative of the surrounding Worcester region, the benefits of access and internet availability outweighed data accuracy. As previously mentioned, representative-ness is less important to this study due to its comparative nature. Meteorological data collected were not reported to any meteorological organizations, thus less-than-ideal siting had no negative consequences.
3.2: Installation and Data Collection

After completing the assembly of 3D-PAWS, the station was installed in the backyard of WPI Dr. Leslie Dodson’s house in Worcester. The 3D-PAWS system was installed directly adjacent to an AccuRite 01024 Pro Weather Station. Because it was not possible to dig holes in the ground for installing mounting posts, aluminum conduit tubes were cemented in a five-gallon (0.019 m$^3$) paint bucket (Figure 39).

Instead of using a solar panel and battery for the 3D-PAWS installation, a 50 ft. (15.24 m) extension cord was run from an outdoor outlet to a 110V/5V USB adapter FIG. The AccuRite weather station did not require an external power source and used four AA batteries and a small surface-mounted solar panel.

After installing the two weather stations they were observed for several minutes. The most notable observation made was the difference between the two anemometers. While the AccuRite anemometer

Figure 39: 3D-PAWS (left) and AccuRite Pro Weather Station (right).
spun freely in even light breezes, the 3D-PAWS anemometer was never seen spinning. Pushing the 3D-PAWS anemometer caused rotation, but the friction of the bearing quickly slowed it to a stop. The AccuRite station, when spun manually, stayed in rotation longer. A second observation of the station was conducted three days after installation. The 3D-PAWS anemometer bearing had become even more difficult to rotate and did not spin easily or freely when pushed manually. The AccuRite anemometer was spinning freely with the wind during this observation.

While no anemometer data was collected from the 3D-PAWS system due to computer code issues, these qualitative observations could allow one to conclude that wind speed data collected from the 3D-PAWS system would not match the data collected by the AccuRite station or accurately reflect the actual wind speed.

For 52 hours after installation the 3D-PAWS system reported data to the WPI 3D-CHORDS online portal. During a later check of the online data it was noticed that the sensors were no longer online, but the Raspberry Pi was still able to be contacted using TeamViewer remote desktop software. The sensors were down for 22 hours before reporting data to the portal again. The cause of this outage was not clear, and the station started reporting before maintenance could be performed. After reporting for several more hours, the 3D-PAWS station stopped transmitting data from the sensors again. Using the Raspberry Pi terminal, the sensors were manually queried, but reported back “IOError: [Errno121] Remote I/O error”.

There were, in total, five days of data collected from 3D-PAWS, but only for the humidity and temperature sensor (HTU21D) and the MCP9008 temperature sensor. The data from 3D-PAWS were collected from January 21 to January 27 (Figure 40).

![Figure 40: Days of data collected by 3D-PAWS. The fourteen days of measurement between 22 December and 5 January were from an indoor test setup of the radiation shield and do not represent meteorological measurements.](image)

The few data points that were collected were graphically displayed on the CHORDS portal. The data visualization options plotted user-chosen weather variables against a range of time (Figure 41).

![Figure 41: Example data plot from the MCP9008. One week of temperature data plotted in both Celsius (blue) and Fahrenheit (black).](image)
The Raspberry Pi remained connected to the internet for approximately one week after data was no longer being reported and could be contacted using TeamViewer. After this week the entire system went offline and could not be contacted. Further analysis of the weather data would have required manual retrieval of the unit and downloading the log files created by the Python code. Due to how intermittently 3D-PAWS reported sensor data it was decided to do no further data accuracy testing. Data acquisition was already unreliable, an issue that should be addressed before determining accuracy.

**Objective 4: Cost Analysis of 3D-PAWS**

This project began under the premise that it would cost between $200 and $400 to produce a single 3D-PAWS system. In addition to evaluating the assembly and installation process of 3D-PAWS, this project also served to assess the cost of the project. The true cost of producing a 3D-PAWS system was calculated by tracking expenses throughout the assembly process.

While purchasing all materials for printing and assembling a 3D-PAWS system at WPI, the cost of every material or tool purchased was recorded in a spreadsheet (Appendix C). The total cost of $698.87 is close to the initially estimated cost of $654.84, however, departs from the predicted cost to build the station at WPI. UCAR’s 3D-PAWS system overview states that, “a very high quality 3D-PAWS surface weather station can be manufactured in about a week, at a cost of only $200-400, using locally sourced materials, microsensor technology, low-cost single board computers, and a 3D printer.” This claim is initially appealing in relation to the cost of commercial weather stations that typically cost in the neighborhood of $600 - $1500.

Given the availability of tools and materials at WPI, the initially estimated cost of assembling a 3D-PAWS was $291.82. However, as assembly progressed, components cost more than expected, or weren’t easily available. Removing the cost of tools, the solar panel, charge controller, and battery, the cost of construction and assembly was $397.13, which falls within the projected cost published by UCAR. However, this equipment is all necessary to operate 3D-PAWS.

If the cost of the 3D printer (the Flashforge Creator Pro is $899) is included in this analysis, the cost of production and assembly was $1,597.87. This does not take into account that not every part of 3D-PAWS could be printed on the Flashforge Creator Pro due to the limitations of the bed size. The Ultimaker 2 Extended+ on which the rain gauge funnel had to be printed (and the funnel rim if it had been printed) because of its large volume has a retail value of $2,999. Assuming only this printer was purchased and used for assembly, the cost of 3D-PAWS was $3,697.87. What was proposed as a low-cost weather station became a significant investment that could pay for several commercial weather stations. The constraints of production should be considered when presenting an estimated the price, or the price estimate updated to reflect the cost of all necessary tools and materials.

The following chapter further discusses recommendations for changes to the 3D-PAWS program that would benefit future installation groups and make for a more user-friendly experience. The project shows great potential as an alternative to conventional means of weather monitoring, but as it is, is not ready for widespread dissemination or publication. These recommendations are made in the hopes that the 3D-PAWS project will reach viability and its potential for installation networks across the globe providing better resolution for weather and climate monitoring.
Chapter 6: Recommendations
Below is a list of recommendations for UCAR to improve their 3D-PAWS initiative.

1. **Printing:**
   a. The 3D printer settings should be provided to prevent a production team from having to run test prints. Though these may not be the immediately perfect settings for a given printer, they would serve as a starting point of reference.
   b. The UCAR website says it is possible to print and assemble 3D-PAWS in one to two weeks. This estimate should be revised, or an explanation of how this timeframe was determined should be added.

2. **Cost:** The UCAR website suggests that a 3D-PAWS installation should cost between $200 and $400. UCAR should provide a cost breakdown of all materials and tools and present a running total for all potential users and producers.

3. **Printed Components:** Throughout the project, many 3D-PAWS components, such as cable components or bolts, could be purchased and not printed. UCAR should outline the benefits of 3D printing all parts and components (if any), and whether or not printing all parts proves to be more time-effective and cost-effective. These parts include:
   a. Cable connectors / cables
   b. Bolts
   c. Inner shaft for radiation shield

4. **Purchased Components:** Several of the components for assembly were not specified in the assembly documents provided by UCAR.
   a. The ball-bearings for the anemometer and wind vane were not specified, and the ones purchased seemed to have too much friction. When placed next to the commercial weather station, the 3D-PAWS anemometer did not spin, while the commercial station spun for very light breezes. The specific bearings that should be used should be specified.
   b. The size of the magnets for the tipping counter and anemometer were not specified and the parts had to be printed and measured before the magnets could be purchased. These specifications should be provided with the assembly document.
   c. The capacitor and resistor legs were too short for use in the soldering jig. The capacitor manufacturer on which the jig was based should be provided so that similar components can be ordered.

5. **Wiring:** The wiring sections should be revised for clearer assembly. Step-by-step instructions are useful, but difficult to follow without clear labeling. The wiring harnesses should have schematics for reference. Specifically:
   a. The common rail assemblies should be eliminated. They take a significant amount of time to assemble, take up a lot of space inside of the radiation shield and the Pi Tube, and could be easily accomplished by simply soldering the wires together and sealing with hot glue or nylon electrical tape.
b. The wiring harness itself has the potential to be reduced to a printed circuit board that
could act as a ‘shield’ on the Raspberry Pi. This would require producing a schematic
layout and transferring it to a circuit board, but the benefit of not having to assemble
the wiring harness by hand would save much time and confusion.

c. The wiring harness sections need a schematic layout for reference. Trying to assemble
the harness simply by color was difficult and required much cross-referencing. The
step-by-step instructions should also specify to which each component attaches on
every step so the assembler doesn’t get confused.

d. The diagram orientations in the assembly document are often rotated 180° away from
the perspective of the assembler. This requires the reader to mentally rotate the image
or sketch down what the circuit looks like before attaching or soldering components.
This is most problematic in the anemometer and rain gauge sensor assemblies.

6. Sensor Software:

a. The best solution to the software coding would be a graphical user interface (GUI)
(even a very simple one) that allows the user to input their specific CHORDS URL
for posting data, which would update that across all of the Python scripts. A GUI for
managing the Chron scheduler program would also be beneficial to the user.

b. The purpose of the Raspberry Pi is exclusively data collection. The folder containing
the scripts for the weather station is buried several directories down in a folder called
“wx_stn”. Moving this to the desktop would make accessing and finding the
documents for editing much easier and would reduce the length of the file location
when trying to execute commands in the command line.

c. The software documentation doesn’t explain how to input the URL into the Python
codes, which is necessary to send the data to the CHORDS portal.

d. The list of basic commands at the beginning of the software documentation is useful
for learning to navigate the Raspberry Pi Linux terminal, but their uses aren’t explained
in the context of the weather station.

e. The documentation should follow more of a user and task analysis approach to setting
up the programs. As the documentation is, the steps required to set up the station are
not obvious or easy to figure out.
Chapter 7: Conclusion

This project focused on printing, assembling, and installing the 3D-PAWS system as designed by UCAR. It assessed the feasibility of 3D-PAWS as an alternative and compared the system to a commercial weather station. UCAR’s 3D printed initiative outlined potential benefits of a 3D-PAWS system: low-cost, reliable micro-sensors, local assembly, and the potential to ‘re-print’ parts should the system fail. UCAR stated on their website that printing and assembly of 3D-PAWS would prove to be both more time-effective and cost-effective than using a commercial weather station. By comparing the data collected by 3D-PAWS and a typical commercial weather station, and the time and cost disparity of assembling and installing both stations, suggestions for changes to the 3D-PAWS project, and feasibility as an alternative to a commercial weather station was assessed.

UCAR’s recommendation was that a total 3D-PAWS installation could be completed in one week and produced within a price range of $200-400. The overall printer runtime and total cost to completely produce, assemble, and install 3D-PAWS far surpassed what UCAR initially recommended. The constraints of production should be considered when presenting an estimated time and cost analysis or should be updated to reflect the time and cost of printing, assembling, and installing all necessary tools and materials.

If it is possible to build and assemble a system within UCAR’s time and cost total recommendations, the 3D-PAWS initiative could be a viable alternative to using commercial weather stations to collect meteorological data. The 3D-PAWS initiative could build capacity to reduce weather-related risk in developing countries, observe and communicate weather and climate information to rural communities, and develop observation networks and applications to reduce weather-related risk.

However, without better organization and documentation for the physical assembly of 3D-PAWS, or significant usability changes to the software-side of the project, the program is not yet viable for large-scale deployment. Given the difficulties encountered during the installation and the disparities in cost and time required, the expectations for producing a system should be reevaluated. In addition to the assembly difficulties, the software side of the program is not clearly documented and not user-friendly. The programs, as they were, did not work for posting data to the CHORDS portal without significant changes to the scripts. It was only possible to get three of the seven sensors to work.

A user-and-task analysis-based approach to the 3D-PAWS program would greatly benefit future production teams, particularly for the software aspects. The physical components by themselves are not particularly difficult to produce or assemble (though take much more time than expected), but the wiring and installation of sensors could also benefit from changes to the assembly documents, particularly by adding wiring schematics or simplifying aspects of production.
Design Statement

This project focused on assembling and installing the University Corporation for Atmospheric Research’s (UCAR) 3D-Printed Automatic Weather Station (3D-PAWS). The University Corporation for Atmospheric Research (UCAR) has started the 3D-PAWS Initiative to expand observation networks in sparsely observed regions of the world. The 3D-PAWS initiative aims to reduce weather-related risk in developing countries, observe and communicate weather and climate information to rural communities, and develop observation networks and reduce weather-related risk.

The approach to this project consisted of four phases: establishing a technical and practical understanding of 3D printing method; 3D printing, assembling, and installing 3D-PAWS; determining a suitable location for installing 3D-PAWS and comparing performance with a commercial weather station; and completing a cost analysis of installing 3D-PAWS. The first step to establish a technical and practical understanding of 3D printing methods was to conduct background research about characteristics and applications of 3D printing. This included learning characteristics and applications of 3D printing, printer specification and use, and filament type. Several trial prints were conducted as part of the preliminary research to determine ideal printing process for 3D-PAWS components.

After establishing a technical and practical understanding of 3D printing, the 3D-PAWS components were printed and assembled. The determined print parameters were used to generate the print code files. The files were then organized and printed. The printer files, or STL files, provided by UCAR were organized by sensor or function groups to correlate to the ten component groups of 3D-PAWS system. Separating the files by sensor or function made accounting for each component manageable and helped expedite assembly. During the printing process, any failures or difficulties were recorded to produce recommendations for changes to the printing process.

The printed 3D-PAWS components were assembled per the UCAR provided assembly instructions. Similar to the 3D printing process, any difficulties encountered were recorded, modifications to the assembly document were made, and recommendations of changes for UCAR were made. After printing and assembly were complete, the 3D-PAWS system was installed adjacent to a commercial weather station with the intent of gathering data simultaneously for comparison.

This project focused on testing 3D-PAWS as a low-cost alternative for obtaining weather data using 3D printed components and small electronic sensors. This testing required designing methods for assessing the usability and reliability of 3D-PAWS. To perform these tests, it was necessary to conduct preliminary research to provide a foundation for developing methods. It was also necessary to design a system for 3D printing, organizing, and assembling the components of 3D-PAWS.

All of the design components fundamental to this project were critical to assessing 3D-PAWS as a low-cost alternative to obtaining weather data and determining the economic feasibility of 3D printing a weather station. This work will provide constructive feedback for improving the 3D-PAWS program so it can be more broadly implemented.
Licensure Statement

Professional Engineering (PE) licensure is a symbol of competence and an assurance of quality for the engineering profession. It is the mark of a professional and is recognized by employers and clients. It shows employers that the employee is competent in his or her profession. Licensure lets clients know that an employee has the credentials and ability to take on a higher level of responsibility, and it gives them a sense of trust in the employee’s work. Licensed engineers are the only ones who can prepare, sign, seal, and submit engineering plans and drawings.

Becoming a licensed PE is a difficult task to achieve and requires a number of steps. First, an engineer must graduate from an ABET-accredited engineering program and pass the Fundamentals of Engineering Exam (FE) to become an Engineer-in-Training (EIT). After becoming an EIT, the engineer must focus on gaining professional experience in the engineering industry. Requirements vary by state, but most require at least four years of engineering experience working under the supervision of a PE. The work completed during this time must be compiled in a portfolio for submission to achieve PE licensure. The final step in order to become a licensed PE is to pass the Professional Engineering Exam.

To an engineer, achieving PE licensure is a mark of his or her qualification and dedication, rewarded with the highest achievement in the engineering industry. Upon becoming a licensed engineer, one must accept the ethical responsibilities that come along with this title. The main responsibility of every licensed engineer is to maintain the public’s health and welfare in every project they approve. This is essential for the public to assume their daily lives with trust that every structure they encounter was designed and approved by a PE. This is also essential to the engineering industry itself. All engineers must adhere to these ethical responsibilities, keeping the profession honest and safe, allowing engineers to serve the public to the best of their ability.

This project involved the evaluation of weather data, and the comparison of weather data collected from a 3D-printed weather station with data collected from a commercial weather station. To accurately produce, collect, and compare reputable data, the assembly and installation of both weather stations would need to be approved by a PE and stamped with a seal of approval. This PE approval ensures that the data collected is accurate and in compliance with all codes and regulations. These codes were created to maintain safety and reputable data; therefore, non-compliance with these codes is not only negligent, but also increased the likelihood for inaccurate data collection and methods. Since this project is an assembly and installation project, accurate guidelines must be followed and can only be assured once a PE has approved the plans.
Works Cited


Appendix A: 3D-PAWS Initiative Brochure

The 3D-Printed Automatic Weather Station (3D-PAWS) Initiative

Improving weather data collection in sparsely observed regions with low-cost technology

What is 3D-PAWS?

Many surface weather stations across the globe suffer from incorrect siting, poor maintenance and limited communications for real-time monitoring. To expand observation networks in sparsely observed regions, the 3D-PAWS (3D-Printed Automatic Weather Station) initiative has been launched by the University Corporation for Atmospheric Research (UCAR) and the US National Weather Service International Activities Office (NWS IAO), with support from the USAID Office of U.S. Foreign Disaster Assistance (OFDA).

Goals of the 3D-PAWS initiative:

- Build capacity to reduce hydrometeorology-related risk in developing countries
- Observe and communicate weather and climate information to rural communities
- Develop observation networks and applications to reduce weather related risk

System Overview

A very high quality 3D-PAWS surface weather station can be manufactured in about a week, at a cost of only $200-400, using locally sourced materials, microsensor technology, low-cost single board computers, and a 3D printer. 3D-PAWS sensors currently measure pressure, temperature, relative humidity, wind speed, wind direction, precipitation, and visible/infrared/UV light. The system uses a Raspberry Pi single-board computer for data acquisition, data processing, and communications.

Benefits of a low-cost 3D-PAWS system:

- Uses low-cost, reliable micro-sensors
- Can be assembled locally at Met Offices or other local agencies
- Components can be “re-printed” when systems fail
- Local agencies take ownership in building and maintaining observation networks
Sensor Evaluation

3D-PAWS is being assessed at the NCAR Marshall Field Site in Boulder, CO, the NOAA Testbed facility in Sterling, VA, and at selected international locations. The Boulder site provides sampling conditions in a high-altitude semi-arid environment with subfreezing temperatures and frozen precipitation (the latter is not measured). The NOAA site provides sampling for a more temperate and humid climate near sea-level. The international 3D-PAWS sites provide an assessment of sensor performance in a variety of tropical and sub-tropical climate regimes.

Station Pilot Networks

3D-PAWS systems have been deployed in the United States (3), Kenya (9), Zambia (5), Barbados (1), and Curacao (1). The primary focus in the United States is on testing and evaluation. The sites in Kenya are colocated with schools with a test site at the Kenya Met Department (KMD). The sites in Zambia are installed at radio stations, schools, and rural missions with a test site at the Zambia Met Department (ZMD). The sites in the Caribbean are located at the Curacao Met Department (CMD) and the Caribbean Institute for Meteorology and Hydrology (CIMH) with the primary focus on testing and evaluation.

Data Access

3D-PAWS real-time data are available on the CHORDS project data servers: http://3d-kenya.chordsrt.com (Kenya), http://3d-zambia.chordsrt.com (Zambia), and http://3d.chordsrt.com (for testing and evaluation). CHORDS (Cloud-Hosted Real-time Data Services for Geosciences) is a US National Science Foundation (NSF) EarthCube initiative to provide a platform for sharing geosciences datasets. It is supported and managed by the UCAR/ National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL).

Benefits, Impacts, and End Users

3D-PAWS observations can be used for a variety of hydrometeorological applications.

Example applications:

- Regional weather forecasting
  Observations from the 3D-PAWS network can be assimilated into regional numerical weather prediction systems such as the Weather Research and Forecast (WRF: http://www.wrf-model.org) model to improve mesoscale weather forecasts.

- Early alert and regional decision support systems
  Real-time monitoring of precipitation in ungauged or minimally gauged river basins can provide input to flash flood guidance and early warning decision support systems to support delivery of flood alerts.

- Agricultural monitoring
  3D-PAWS can support water resource management tools to improve reservoir operation for fresh water supplies and the generation of hydroelectric power. Other applications include operation of irrigation systems (e.g., center pivots) and agricultural crop monitoring.

- Health monitoring
  3D-PAWS can help monitor conditions leading to outbreaks of diseases such as meningitis and malaria.

Contact

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Appendix B: Raspberry Pi and Sensor Descriptions

The Raspberry Pi 3 Model B is the third-generation Raspberry Pi and was released in February 2016. It offers a Quad Core 1.2GHz Broadcom BCM2837 64bit CPU, 1GB RAM, onboard Bluetooth, and wireless local area network (LAN), a 40-pin extended general-purpose input/output (GPIO), 4 USB-2 ports, and a HDMI output [20]. The GPIO connector provides 26 GPIO pins and +3.3V, +5V and ground (GND) supply lines [20].

Sensor outputs can be analog or digital, which changes the way data is received and read by the Raspberry Pi. Analog signals are smooth, continuous waves that have “gentle” voltage transitions between low (0 V) and high (+3.3 V or +5 V), while digital signals alternate between “on” and “off” and appear as a square wave [21]. Serial peripheral interface (SPI) and Inter-integrated circuits (I²C) are serial busses that communicate through digital signals. This allows communication between multiple master-slave chips. Two wires can serve up to 127 devices, where each device has a unique identifier that the master uses to recognize the slaves. For these two-wire systems, one wire serves as a serial clock line (SCL) while the other serves as a serial data line (SDA). The SCL synchronizes data transfer between the devices while the DDA transfers the data [21].

The Honeywell SS451A Bi-Polar Hall Effects Sensor is a Hall effect sensor that can be activated by either a north or south pole. The sensor has an operable temperature range of -40 °C (-40 °F) to +150 °C (302 °F) and tolerates a maximum input voltage of 24 V. At 12 V and 25 °C (77 °F) the sensor’s output switching time (state changing from operating to release) is 1.5 µs. The output is analog [22].

The BMP280 is an absolute barometric pressure sensor designed for mobile applications. The sensor is based on piezo-resistive technology sensor. It has an operational range from 300 hPa (8.85 inHg) to 1100 hPa (32.5 inHg) and 0°C (32 °F) to 65 °C (149 °F) with an absolute accuracy of +/- 1 hPa (0.029 inHg). The BMP280 offers I²C, SPI digital, and serial interfaces [23].

The MCP9809 is a digital temperature sensor designed for general purpose applications. The sensor has an operable temperature range of -40 °C (-40 °F) to +125 °C (257 °F) with a +/- 1°C (1.8 °F) resolution over the entire range. The sensor uses I²C as a digital interface [24].

The HTU21D is a digital relative humidity sensor with temperature output. The operable range of the HTU21D’s temperature sensor is -40 °C (-40 °F) to +125 °C (257 °F), and the operable range of the humidity sensor is 0 to 100% relative humidity. The accuracy of the relative humidity over a range of 20% to 80% at 25 °C is +/- 3%. The sensor uses a serial clock input (SCK) or serial data line to transfer data [25].

The SI1445 is a low-power, reflectance based, infrared proximity, ultraviolet (UV) index, and ambient light sensor. The sensor is operable from -40 °C to +85 °C and the UV index reported is as standardized by the World Health Organization as weighted by the CIE Erythemal Action Spectrum. The sensor uses an I²C interface to communicate with a processor [26].

The Littelfuse 55300-00-02-A Flat Pack Rotary Sensor is a rotary absolute position sensor that provides an angular measurement between 0 and 360 degrees. The unit is activated using a remote magnet using non-contact magnetic Hall effect technology. The sensor has an operating temperature range between -40 °C and 105 °C and an accuracy of +/- 4 angular degrees. The sensor uses an analog interface to communicate, indicating a voltage between 0.5 V and 4.5 V given angular position [27].
### Appendix C: 3D-PAWS Material Costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>32GB Micro SD</td>
<td>1</td>
<td>$15.60</td>
<td>$15.60</td>
</tr>
<tr>
<td>0.025&quot; Magnets (100 Pack)</td>
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<tr>
<td>1&quot; PVC 45° Elbow</td>
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<td>$1.14</td>
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<tr>
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<tr>
<td>1&quot; PVC Tee</td>
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<tr>
<td>1&quot; x 10' PVC Pipe</td>
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<td>$7.82</td>
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<tr>
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<td>$1.14</td>
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<tr>
<td>1/2&quot; Arch Punch</td>
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<tr>
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<tr>
<td>1120 Piece Resistor Kit</td>
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<td>12 Gauge Silicone Wire</td>
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<tr>
<td>200-Grit Sandpaper</td>
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<tr>
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<tr>
<td><strong>Total Cost</strong></td>
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