Aerial Weather Stations and the Quest to Understand Built Environments

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Abstract: This paper responds to the growing desire to systematically gather environmental feedback in cities through the deployment of networks of connected sensors which collect and transmit data, to register change, uncover trends and diagnose potential environmental threats. However, we recognise the novelty of such information gathered and its perceivably limited application in the design decision process. We hypothesise that with the advent of affordable weather sensors, designers will be able to develop custom data capture solutions to improve city scale weather file data. In order to test this hypothesis, the paper investigates the possibility of using a remotely piloted aircraft system (RPAS) equipped with lightweight climatic sensors to refine representative city scale environmental data. First, we reflect on issues of accuracy and site specificity, and discuss whether our access to low cost sensors might liberate our dependency on weather data files. Second, we illustrate how such data may aid in serving the designers to make sense of local micro-climatic phenomena. We conclude with a summary of considerations based on a case study conducted in Melbourne, Australia.

Keywords: Micro-climates, drone, UAV, RPAS, remote sensing, ESD, data capture

Nomenclature:

BMP180	Digital-output pressure sensor
CFD	Computational fluid dynamics
DHT22	Digital-output relative humidity and temperature sensor
EPW	EnergyPlus weather file
ESD	Environmentally sustainable design
RPAS	Remotely piloted aircraft system(s)
TMY	Typical meteorological year
TSL2561	Digital-output luminosity sensor
UAV	Unmanned aircraft system(s)

1 Introduction

The quest to understand built environments has resulted in a number of tools and toolkits that enables designers to make sense of big data such as climate information (MACKEY et al. 2018). In response to a growing desire to gather systematic environmental feedback, cities are investing in a variety of data collection means. This can include deploying networks of connected sensors which collect and transmit data, to register change, uncover trends and diagnose potential environmental threats. Despite ongoing efforts and a desire to apply climatology at the landscape architecture scale, MELSOM et al. (2017) note that is still uncommon to reflect the advent of on-site sensing and analysis, citing publications that document digital techniques and landscape architecture (WALLIS & RAHMANN 2016). To date, the application of climate studies largely remains as a novel approach to inform design making solutions. HEBBERT (2014) outlines disappointments in the progress of applying climate driven approaches in city planning and outlines four factors, namely 1) the limitations of international standardization; 2) indifference on the part of national meteorological agencies;

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3) unreceptiveness of urban decision-makers; and 4) the changing character of the science itself. Should we consider meteorological information as a resource to inform our design decisions, why is this unreceptiveness largely prevalent within the design discourse?

HEBBERT (2014) cites the work of Rudolf Geiger as an example of how the diffusion of techniques in climate mapping originated in viticulture and were developed in the context of agricultural and forestry research. GEIGER (1965) saw the map as the synthesis of field-worker's long immersion in a landscape and in turn its application by municipalities transformed the technique into a translation device – a methodology usable for public planning purposes. *Klimaatlass* which simplifies and render legible those aspects of the urban climate effect that are relevant to human health and comfort. Hebbert elaborates:

*"The aim is not to optimize for a particular weather event, but to avoid harm, encourage flexibility for an uncertain energy future, and create variety of climates that will be serviceable in all seasons (*SCHERER et al. 1999*). Klimaatlas method seeks to give decision-makers – as Edward Ng puts it – an 'actionable understanding' of their air resource* (NG 2011)*."*

Recent attempts of an 'actionable understanding' of climate information for design is demonstrated by how designers have begun to operationalise weather data typically written into EnergyPlus weather (EPW) files. These rich data sets contain hourly resolution data points for an entire typical meteorological year (TMY), i. e. 8760 points for a large range of environmental variables. These data are typically captured at airport weather stations, which can be expected to have different local environments than sites within the city, which may be subject to the heat island effect, higher wind turbulence and pollution levels. Designers rely on the EPW data through the use of the Ladybug Plugin in Rhino/Grasshopper to support the decision-making process during early stages of design (ROUDSARI et al. 2013). However, the data is only representative and does not include site-specific, locally varying micro-climate phenomena (BOURIKAS et al. 2016).

This paper attempts to tackle this perceived *unreceptiveness* through the following matters:

1) A matter of accuracy and site specificity: Given our ability of using low cost sensors to capture an increased spatial resolution of environmental data, to the point where differences in micro-climate observed in between street corners, can be recorded by custom made capturing devices, does this agency allow us to liberate our dependency on weather data files?
2) A matter of the designer's intent: How do we make sense of our observations of these micro-climate phenomena at the precinct or building scale and make it relevant to design decisions?

We hypothesise that with the advent and opportunities provided by affordable weather sensors, designers will be able to develop custom data capture solutions to improve weather file data for urban environments. In order to test this hypothesis, the paper investigates the possibility of using a non-autonomous, remote pilot aircraft system (RPAS) equipped with lightweight climate sensors to refine representative city scale environmental data as a means to inform architecture and landscape design decisions. An initial case study conducted in Melbourne, Australia is presented.

2 Aerial Weather Station

2.1 Site Context

The case study was conducted at Siteworks, a community facility in Brunswick, Melbourne. The Italianate style heritage house on site was the former residence of Alfred Cornwell, the proprietor of a major pottery and brick works in Brunswick. Today, the site welcomes projects and initiatives that can inform the future development of the site by hosting galleries and educational events. It sits outside the north of the City of Melbourne and within the south end of the Moreland City Council. Its proximity to amenities such as the community swimming pool, shopping street and train station makes it ideal for future development to take place.

2.2 Custom Prototype

Historically, the term 'drone' refers to an unmanned aerial vehicle (UAV) largely used for military purposes. The early 2000s saw an emergence of cheap consumer drones for recreational purposes, while more recently interesting commercial uses have started to emerge in the middle. Between 2016 and 2020, an estimated 17.1 billion USD will be spent on UAV surveying in construction and agriculture (GOLDMAN SACHS 2017). For the most part, UAV data capture has been used to collect visual information with cameras, in the visible electromagnetic spectrum as well as to a lesser extent thermal, multispectral and hyperspectral imaging. Rarely are UAVs equipped with sensors that measure properties of the air itself, such as ambient temperature, humidity, or wind speed.

Urbanisation is a defining global trend that is especially characterised by a vertical expansion of the built environment. Design briefs have increasingly higher standards for sustainability and human comfort. There is a growing need to design tall buildings that interact more effectively with their own immediate environments. While the zones of interest for human comfort are at street level and near the building envelope, in a complex and turbulent urban environment a deeper understanding of the origins of observed effects is required to react more to inform the design process. In these cases, volumetric data may help designers plan cities and buildings in a more environmentally informed manner.

Fig. 1:
Environmental sensors propped by a 3D printed stand attached to the DJI Mavic aircraft

Since traditional terrestrial sensing platforms are impractical to map volumetric data, an RPAS equipped with lightweight climate sensors was chosen as a mobile, aerial sensing device. An initial sensor platform was prototyped from Arduino microelectronics modules (Table 1) and fitted with sensors measuring temperature, humidity, luminosity and air pressure (Figure 1). These were logged and time-stamped at one second intervals to an on-board SD card. Positional data was obtained from the drone's flight log. The result from a corresponding aerial photogrammetry campaign was used to produce a 3D site model. Considering that the application of this method is intended for designers, a workflow was developed to display the sensor values as color-coded spatial points within the 3D modelling software Rhino/Grasshopper, in which the 3D model served as a context for the spatial location of the data points (Figure 4).

Table 1: Sensor specifications

Sensor	Measured variables	Accuracy	Resolution	Weight
DHT22	Temperature Relative Humidity	0.2 Celsius 2-5 % RH	0.1 Celsius 0.1 % RH	2.5 g
TSL2561	Luminosity	Varies	0.1 lux	1 g
BMP180	Barometric pressure Temperature	ca. 0.06 hPa ca. 1 Celsius	0.01 hPa 0.01 Celsius	1 g

3 Results

This study was an attempt to test a workflow for environmental RPAS data capture, and to identify the strengths and weaknesses of such a methodology. It was also attempted to scope out which sensors would provide the most meaningful insights for design purposes. This initial study site covers approximately 0.4 hectares. The flights were conducted on two afternoons in August, a week apart. The results show short time frames of data, displayed as dots at their relative locations in the 3D model (Figure 2).

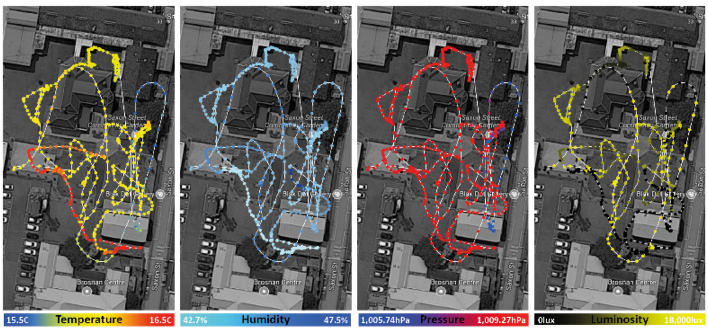

Fig. 2: Geolocated temperature, humidity, pressure and luminosity readings

The spatial variation is emphasized over the temporal; this contrasts the way that climate data is most commonly displayed, namely as a linear 2D graph with time on the x axis. Doing so (Figure 3) allows the designer to get a better sense of the accuracy and correlations between data points, for example:

- An increase in elevation of the drone is clearly visible through a drop in the pressure reading. This coincides with a decrease in temperature, which can be expected due to reduced radiant surface temperature with distance from the ground;
- The two temperature sensors used (DHT22 and BMP180) differ by ca. 1K. While the BMP reading is smoother due to higher resolution, the DHT22 reading is more reliable in terms of accuracy as described by the data sheets;
- The luminosity sensor had less than half the range specified in its data sheet, as can be seen by the sudden drops to 0 after the luminosity climbs to a certain point;
- Overall the visualisation allows the designer to manage their expectations of accuracy of the equipment;
- The variance of most environmental variables is very small at this scale (e. g. 1.1K for the DHT22 temperature reading).

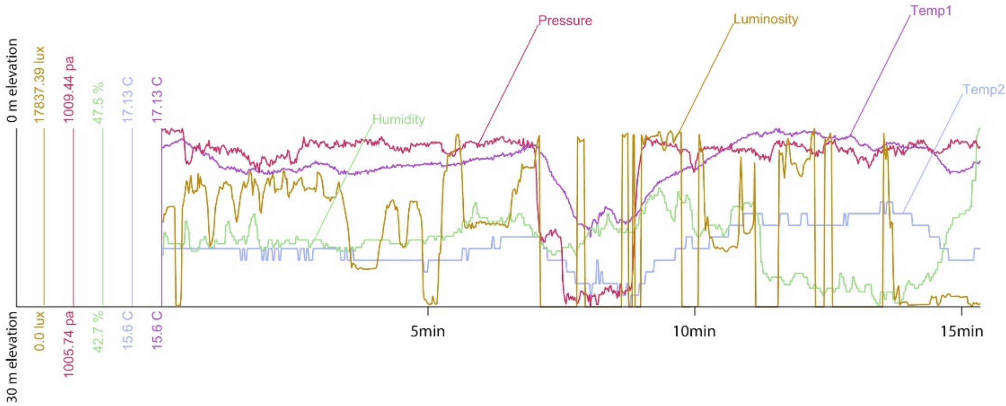

Fig. 3: Linear plot of sensor readings during the flight

Viewing both visualisations in comparison allows the designer to reflect upon the data and set up hypotheses. For instances, the decrease in temperature correlates not only with an elevation difference but was also mapped above a vegetated area of the site. A further investigation may therefore verify the effects of the vegetation on the micro-climate, as well as measuring the radiant heat emitted by the surrounding surfaces.

Provided that the amount of visualised data was kept to a minimum, the authors perceived a three-dimensional visualisation (Figure 3) to further aid in spatially understanding site characteristics. The flight portrayed here involved capturing data underneath the tree crowns. Here a temperature decrease was detected, which matched the findings of the earlier flight.

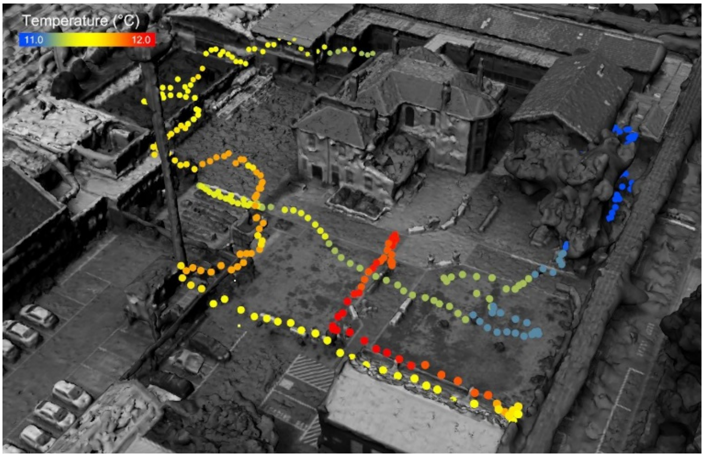

Fig. 4:
(Left) False colour rendering of the temperature recorded embedded within the digital surface model and (Right) Insert image of model + EPW data

Micro-flight data capture is intrinsically limited temporally, in this case 15 minutes per battery. In addition to the limited UAV endurance, flight permission was only given for two days. The results allow for an initial, exploratory engagement with site-specific data capture, provided that the viewer is aware of the accuracy of the sensors and limited temporal length of the data set. At the scale of the provided case study, it was to be expected that most environmental variables exhibit little variance since the air is well mixed. In this scenario, terrestrially mounted sensors may have been more effective given their ability to log time-varying and reliable data. For UAV usage, this method will be further investigated in future at larger scale sites. As a climate variable with higher three-dimensional variance, wind speed and direction will be incorporated into future studies.

4 Discussion

A desired outcome of this method is to create a flexible, easy way to record and visualise custom captured environmental data, thereby raising environmental awareness during the design process and promoting sustainable design decisions. The significance of the work presents opportunities for research into the performance and evaluation of the existing built environment from the precinct to the building scale. This would be especially pertinent in generating design scenarios that observe the trajectory of city making defined by infill development and redevelopment projects.

4.1 A Matter of Accuracy and Site Specificity

In this paper, it was hypothesised the weather file may not always be representative of the local micro-climate on site. The site may lie within the city and therefore be affected by the urban heat island effect and subject to high levels of pollution and wind turbulence, while the weather station capturing the weather file data is often located at airports on an open field outside the city. Therefore, custom data capture may in some cases be crucial for accurate energy modelling. To quote Erik Olsen, director of Transsolar Climate Engineering:

"*If you're in a situation where there's very little local climatic variation, then the generally available weather data – TMY data – is usually pretty valid. [...] However, if you're in an area where the typography is extremely varied, the generally available weather data is probably incorrect, because of the elevation changes, or you're in a valley but the weather station is not. Then, more local data becomes extremely important.*" (DEUTSCH 2015)

As other research has demonstrated previously (WONG et al. 2013), environmental data capture – be it terrestrial or aerial – may help in a number of ways during the site inspection. High resolution site data may help in the decision-making process for planting schedules and the determination of a likely irrigation method. Accurate outdoor comfort analyses may support the design of wind breaks and shading devices. For instance, Fig. 4 suggests illustrates the temperature difference between open and vegetated spaces; together with a solar radiation analysis (Fig. 1), the designer may consider shading canopies near the centre of the plot.

Data capture needs to be considered an additional source of environmental data, viewed in combination with existing data sources. In some cases, weather station data may be insufficient to describe on site weather conditions. An example for this is when the site lies within a valley while the nearest weather station is on higher ground (DEUTSCH 2015). Another example is when considering sites exposed to the urban heat island effect. While some methods help to simulate this effect more accurately (UNZETA 2007), additional data capture may be useful as a means of validating the simulation. Furthermore, the described capture of ambient environmental data may be combined with further types of data; combined with on-site vegetation analysis, this may lead to the study of its effects on the local micro-climate. Terrestrial laser scanning may further help in relating this to vegetation volume.

The case study site described in this paper was identified to be largely unsuitable for the use of aerial data capture. The site is at a similar altitude as the nearest weather station and is not influenced by significant changes in topology. The site and its surroundings is characterised by uniformly low-rise buildings. For all intents and purposes, any additional climate data needed would be measured close to the ground and buildings and would therefore not warrant the use of RPAS. For larger sites more suitable for RPAS usage, the RPAS may be useful for quick, large scale sweeps of the area to gain an initial understanding of potential zones of interest, in which to conduct further investigation. In any case, the goal of the mission is to be determined before flight in order to increase the efficiency of the investigation. This may constitute the hypothesis of zones with problematic wind or temperature phenomena based on existing heat sinks and obstacles.

4.2 A Matter of the Designer's Intent

A differentiation must be made between *pre- and post-construction analysis.* Data capture prior to construction may be used as a method to create energy and comfort models with higher local accuracy, while post-construction analysis may in turn be used to validate design intent and feed into the design process for further developments. In city districts of uniform topology and a large amount of future infill developments, introducing pre- and post-construction data capture may feed into building a database of lessons learnt to be used in future design briefs for buildings within the vicinity.

Due to the small size of the site, the variance of most climate variables can be expected to be low. An exception to this is wind. Wind sensing is a promising application for environmental sensing with drones due to its spatially and temporally strongly varying nature. This makes it notoriously challenging to model accurately using computational fluid dynamics (CFD) software. Initial studies have been conducted to test the feasibility of various sensors and UAV platforms for this purpose (FISHER et al 2016, Mohamed 2016, Prudden et al 2016 & 2017). Bespoke wind data collection could provide valuable feedback for design and operational analysis. Applications for drone-mounted wind sensors could include mapping vertical wind profiles upwind of a site in order to inform CFD modelling assumption. It could also entail verifying the presence of predicted wind phenomena such as vortices, eddies and wind tunnel effects, in order to mitigate comfort issues through the design of porous wind screens, planting of vegetation, or wind baffles for downdrafts from facades.

We have summarised a number of considerations for the designer to optimise the outcome of an aerial data capture. The main obstacles to implementing such a method are the following:

- *Limited endurance:* A disadvantage of lightweight RPAS is their short flight time due to limited battery capacity. A standard multi-rotor UAV has a flight time of ca. 20min, fixed-wing UAVs ca. 1h. This is insufficient to map most environmental variables in a way that can support energy and comfort simulations which rely on much longer time-varying spans of data. Further research will investigate to what extent the combination of fixed terrestrial sensors with aerial mapping can enable the accurate prediction of volumetric data, based on the high temporal resolution of the fixed sensors and the limited availability of aerial data.
- *Sensor price and accuracy:* Low-cost sensors were used for the case study. While these are lightweight, their accuracy cannot be guaranteed. High end, accurate sensors are often associated with a considerable increase in cost. They are also often larger and heavier, making them unfeasible for RPAS usage. For example, standard wind sensing equipment includes wind vanes. These are unsuitable for RPAS; a more suitable but costly sensor is a cobra probe as used in PRUDDEN et al. 2016).
- *Regulations:* Flight regulations for RPAS in Australia is prohibitive. The possibility of autonomous, swarming UAVs is thwarted by the fact that regulations require one pilot per aircraft to be present during flight within line of sight.

5 Next Steps

This method is to be tested on large scale sites with a higher expectation of volumetric data variance. Data capture must be conducted for larger periods of time over regular flights in order to validate the feasibility of the method. Other forms of environmental data are to be investigated. In particular, wind phenomena are to be mapped to inform and validate computational fluid dynamics models. Future case studies will be conducted with additional terrestrial sensors for ground truth and continuous data collection.

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