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Introducing the SAMBA indoor environmental quality monitoring system

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Abstract: To date the sustainable commercial building sector in Australia has focused primarily on energy, due in large part to the mandatory disclosure provisions of the National Australian Built Environment Rating System (NABERS). Other dimensions of building sustainability such as Indoor Environmental Quality (IEQ) are less well developed. But widespread concerns about occupant productivity is shifting the spotlight onto building IEQ performance. Our new approach to IEQ measurement centres on small, low-cost, desk-based monitors (SAMBA) with sensors for thermal comfort (air and radiant temperatures, air speed and humidity), acoustics (SPL), lighting (lux) and air quality (CO_2, CO, TVOC, Formaldehyde and PM10). Low unit costs make it feasible to place SAMBAs in each HVAC zone of complex commercial buildings. The SAMBA network architecture is based on a self-forming mesh network that does not require access to the host organisation's ICT infrastructure. Measurements are relayed wirelessly to a central SAMBA gateway within the building that transmits data through the cellular network to the IEQ Laboratory's server every 15 minutes. Various IEQ indices and compliance metrics are calculated in real-time before being presented to an online IEQ dashboard to which the building operator has access.

Keywords: Indoor environmental quality; acoustics; indoor air quality; thermal comfort.

1. Introduction

In the past couple of years the Australian commercial building sector has begun paying more attention to Indoor Environmental Quality (IEQ) issues largely because indoor environment is believed to impact productivity and performance of office workforces. Even though the scientific evidence of this link remains highly contentious (e.g. de Dear et al., 2013) there seems little doubt that more satisfied building occupants with higher levels of wellbeing generally translate into better outcomes for the organizations leasing the building (e.g. Newsham, Veitch, & Charles, 2008). Sustainability rating tools such as Green Buildings Council Australia's "Green Star - Performance" (GBCA 2015), and the National

Australian Built Environment Rating System "Indoor Environment" (NABERS 2015) specifically assess indoor environmental quality of buildings using two broad strategies – occupant questionnaires called Post-Occupancy Evaluations (POE), and instrumental measurements. The latter are retained simply because of the lingering suspicion that non-building issues such as industrial relations, staff morale etc may also influence how an office population will rate their workplace environment on a POE questionnaire. Instrumental data are seen as "ground-truthing" subjective evaluations captured by POE. Measurement of IEQ inside a building reduces to a **spatio-temporal sampling problem**. Many of the key IEQ parameters are characterised by significant variability in spatial and temporal dimensions, and to accurately capture that variability in a sample of instrumental IEQ measurements inside a building poses several technical and logistical challenges.

The **spatial scale** of IEQ variations can be at the HVAC zone level (perimeter versus core zones, east versus west zones in morning and afternoon, north versus south zones in summer versus winter). Some IEQ parameters demonstrate variances on an even smaller spatial scale, for example, in terms of metres in the case of air speed which is directly related to air-supply vents and the often complex flow patterns within a room filled with air. Specific IAQ parameters such as Total Volatile Organic Compounds (TVOC) can also demonstrate sharp spatial gradients and variations, depending on proximity to individual emission sources such as cleaning detergents, particular pieces of furniture, or even particular fit-out materials such as drapes. Mean radiant temperature within a space can also demonstrate significant spatial heterogeneity, depending on proximity to heat-emitting appliances such as computer terminals or photocopiers, or complex and changing patterns of direct solar penetration onto the building floor-plate through large expanses of un-shaded perimeter glazing that is so popular in contemporary office building architecture. Indeed, it was this inherent spatial heterogeneity of mean radiant temperature that was successfully used to argue for the exclusion of that parameter from the NABERs Indoor Environment rating scheme (2015), despite the fact that mean radiant temperature is as important as air temperature in determining human thermal comfort sensations (ASHRAE 2015).

As with spatial scales, the **temporal dimension** of IEQ parameters within buildings is characterised by considerable variability, including cycles and random variations across multiple timescales ranging from second-to-second turbulence, through diurnal cycles, up to synoptic-scale changes in the daily weather conditions outside the building, up to seasonal-scale variations in solar position, deciduous tree shading, and general outdoor meteorological environment. Air temperature time-series within office buildings demonstrate complex ebbs and flows as HVAC systems start-up and switch-off at either end of the working day. Likewise with indoor air quality bellwether parameters such as CO_2 concentrations that reflects the tidal flows of building occupants at the start, middle and end of the working day. The mix of daylight to artificial lighting inside a building responds to the sun path arc from one side of a building to the other through the course of a day, and the background noise level inside a contemporary sealed-façade office building is overwhelmingly dominated by occupant density that fluctuates wildly throughout the day.

2. Previous instrument solutions to the IEQ sampling problem

In view of the inherent spatial and temporal heterogeneity of IEQ parameters within a building it is perhaps surprising that some IEQ rating tools have deemed a one-day sampling strategy to be sufficient to characterise the indoor environmental quality of a building. For example, Australia's NABERS IE (2015) allows a consultant to do a one day walk-through sample of the key IEQ parameters on a random selection of floors in morning and afternoon periods. Apart from missing many if not most of the spatio-

temporal variability described above, a one-day on-site measurement campaign encourages the unscrupulous building operator or owner to "game the system" i.e. temporarily optimise the building management system settings for the duration of the measurement campaign and then revert to less-than-ideal settings in order to minimise energy consumption once the IEQ rating has been made.

The ASHRAE/USGBC/CIBSE Performance Measurement Protocols (PMP) (2010) prescribes three levels of measurement detail: *Basic*, *Intermediate* and *Advanced*. Instrumental measurements prescribed in the Basic protocol include spot measurements with a hand-held temperature, humidity, air speed, illuminance and sound pressure level meters. The *Intermediate* PMP protocol requires time-series (datalogger) observations of air and mean radiant temperatures, relative humidity, occupied zone air speed, CO^2, and vertical plus horizontal surface light-level measurements. The required acoustic measurements include sound pressure level with parallel octave band filters and a noise source for calculation of background noise and reverberation time respectively (Kim, 2012). The *Advanced* PMP level (ASHRAE 2010) requires air and radiant temperatures, humidity, air speed, CO^2, PM2.5, and TVOCs sensors to be logged continuously for a defined period, while the requisite lighting measurements include a High Dynamic Range (HDR) camera and software. *Advanced* PMP requires a sound pressure level meter equipped with a parallel one-third octave band filters and loudspeakers for evaluations of speech privacy, speech communication, sound and vibration isolation respectively (Kim, 2012).

IEQ researchers have developed a variety of solutions to the problem of registering spot measurements inside buildings. Typically they have involved a mobile cart of some sort with an on-board data-logger into which the various transducers have been wired. The cart is typically wheeled around inside the building and the data-logger is randomly triggered to perform a sweep of all transducers. Figures 1 and 2 depict some examples of various carts from the recent research literature.

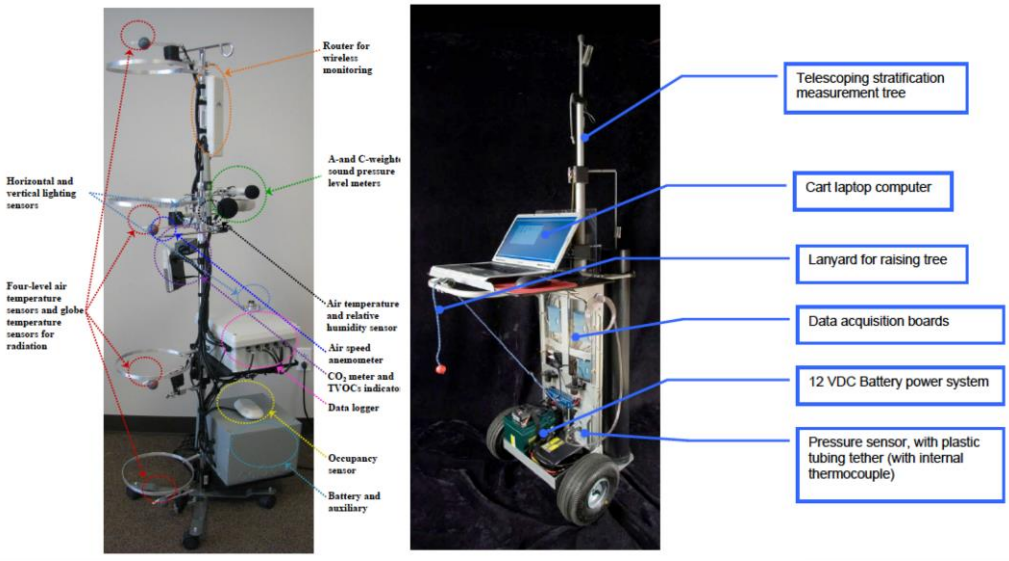

Figure 1: Left - a mobile IEQ cart used to field-test the ASHRAE/USGBC/CIBSE performance Measurement Protocols (Kim, 2012); right - a mobile IEQ cart with telescopic mast of temperature sensors designed to specifically commission underfloor air distribution systems (Webster et al., 2007).

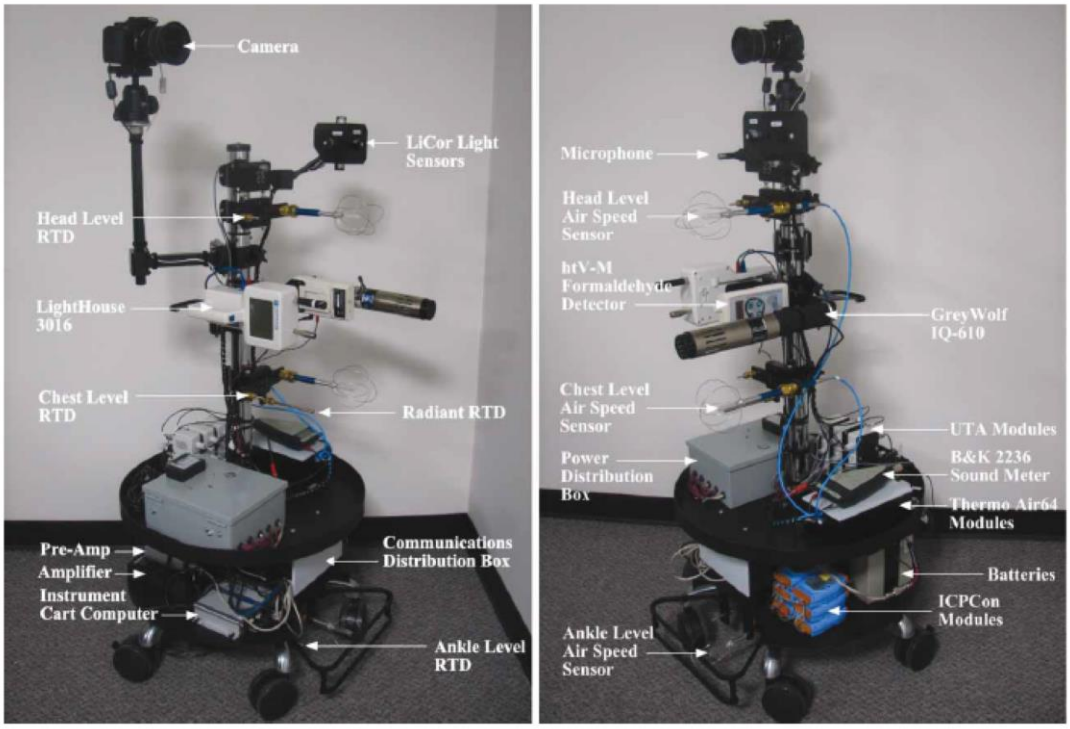

Figure 2: Perhaps the most sophisticated mobile IEQ cart to date includes most transducers required by the ASHRAE/USGBC/CIBSE PMP Advanced Level protocol (Newsham et al., 2013).

In all these mobile cart examples (Figures 1 and 2) the design strategy has simply been to select off-the-shelf, laboratory-grade instruments for each one of the individual IEQ parameters of interest, and then hard-wire them into a centralised datalogger. The end result, without exception, has been a prohibitively expensive apparatus that requires a human operator to wheel through the space and to periodically trigger the datalogger to sweep all of the transducers, time-stamp their data, and store it all in memory for safe retrieval after a day "on the job." The prohibitive expense of this IEQ measurement solution arises from three main causes;

- The individual off-the-shelf instruments themselves are usually exorbitantly priced because of the relatively small market, even if the actual transducer component being used is abundantly available and modestly priced (e.g. a turnkey hand-held CO^2 instrument can easily cost two orders of magnitude more than the actual non-dispersive infra-red sensor component at its centre).
- Mobile IEQ measurement carts require a human operator to steer them along their "random sampling trajectory" within a building. The labour cost, including associated on-costs such as worker insurance and payroll tax, for a technically skilled engineer or research assistant conspire to make each day on-site a very expensive proposition.
- Logistical complexities (inter-city air freight or even just intra-city road transport) and the associated insurance costs of placing an elaborate and extremely delicate scientific apparatus

(e.g. Figures 1 and 2) on-site, all add significantly to the overall costs of a day of IEQ sampling inside a building.

As a result of these factors, measurement of a building's IEQ is prohibitively expensive and beyond the reach of most building owners in the Australian commercial buildings sector. There are only a handful of IEQ consultants operating in the Australian market and the mainstay of their business is collection of the requisite data for NABERS IE ratings. But the demand for NABERS IE ratings has been very low since its inception, prompting the NABERS organisation to fundamentally redesign the IE rating protocol in 2014/15 (NABERS, 2015). The stated aim of that review was to reduce the costs of collecting the IEQ data and applying for the IE rating.

3. Introducing SAMBA IEQ monitoring stations

The basic aim of the SAMBA project (Sentient Ambient Monitoring of Buildings in Australia) was to design a small, low-cost, autonomous IEQ monitoring device that could be placed permanently at multiple sampling points across the occupied zone of a building floor-plate (spatial sampling) and on multiple levels of a multi-storey building (vertical sampling). Permanent placement of such devices could allow longitudinal measurements through time (i.e. all occupied hours for weeks, months, seasons or even years). In this way it is possible to collect a truly representative picture of a building's IEQ performance – not just on "a good day."

The expected Australian end-users of such a system for IEQ performance monitoring and improvement include, but will not be limited to;

- Building owners seeking market advantage in the highly competitive commercial property sector (includes portfolio and individual building owners).
- Commercial building tenants seeking to ensure that the building they are leasing is providing an indoor environment at a quality level specified in their lease.
- Building services engineering firms.
- Architectural and interior design firms.
- Office fit-out firms.
- The Property Council of Australia.
- Green Building Council of Australia (Green Star-Performance).
- National Australian Built Environment Rating System (NABERS Indoor Environment).
- Facilities Management firms and consultants.
- Building services and FM accredited assessors for NABERS IEQ and Green Star-Performance.

3.1. SAMBA's sensors

Decisions about which sensors to include in SAMBA were made largely on the basis of the specifications in Australia's NABERS Indoor Environment (IE) rating tool (2015), but also on component costings. The list of IEQ parameters can be found in Table 1 and cover the four key IEQ areas of thermal comfort, indoor air quality, lighting and acoustics. The SAMBA hardware design integrates a low-cost suite of sensors into a small monitoring station that is intended to be placed on the desk surface (i.e. occupied zone) in a random selection of workstations throughout the building. Rather than focusing on laboratory-grade measurement practices which are appropriate for detailed workplace health audits and perhaps forensic investigations (see Figures 1 and 2 above), SAMBA's sensing capabilities have been

scaled to the application at hand – 'good-enough' real-time data – thus allowing very substantial reductions in both hardware costs and also on-site technical personnel costs.

3.2. Calibration of SAMBA's sensors

SAMBA comes with the caveat that it is not intended to be a laboratory-grade IEQ data acquisition system. Referring to the ASHRAE/USGBC/CIBSE nomenclature for performance measurement protocols SAMBA would qualify at the BASIC measurement protocol, with parts of the INTERMEDIATE protocol covered as well. SAMBA definitely would not withstand legal scrutiny in a forensic context. Nevertheless we have conducted a series of in-house calibration of the SAMBA sensors against laboratory-grade reference instruments across the range of parameters reasonably expected inside office buildings (Kim, 2012). On the basis of explained variance (R2) of the relationship between SAMBA sensor and the relevant calibrated laboratory-grade reference instrument listed in Table 1, the suite of sensors selected for SAMBA are consistent with the performance specifications of ASHRAE/USGBC/CIBSE Basic Level (ASHRAE 2010). To safeguard against calibration drift, the SAMBA device is swapped over, new for old, at the end of every 12 months in service. Each new SAMBA device is laboratory-calibrated using the reference equipment described in Table 1 before being sent out into the field.

Table 1: The suite of transducers selected for SAMBA and their calibration performance against relevant laboratory-grade reference instruments.

Parameter	SAMBA Transducer Type	Measure-ment Range	Resolu-tion	Accuracy	Calibration Reference Instrument	Calibration R^2
Air temperature	NTC thermistor	-40 to 125°C	0.04°C	±0.3°C	Innova 1221 Comfort Logger w/ MM0034 air temperature transducer	0.99
Relative humidity	Capacitive humidity sensor	0 to 100%	0.1%	±2%	Innova 1221 Comfort Logger w/ MM0037 air humidity transducer	0.98
Globe temperature	NTC thermistor	-40 to 125°C	0.04°C	±0.2°C	Innova 1221 Comfort Logger w/ MM0034 air temperature transducer	0.99
Air speed	Hot-wire anemometer	0 to 2m/s	0.01m/s	±5%	Dantec 54T21 omni-directional anemometer	0.98
Carbon dioxide	Non-dispersive infrared	0 to 5000ppm	1ppm	±30ppm ±3%	CET AST-IS infrared CO2 sensor	0.97
Particulate Matter	Photodiode	0.001 to 1 mg/m³	0.001mg/ m³	-	TSI Dusttrak II Aerosol Monitor 8532	0.99

Parameter	SAMBA Transducer Type	Measure-ment Range	Resolu-tion	Accuracy	Calibration Reference Instrument	Calibration R^2
TVOC	Photo-Ionisation Detector	0.001 to 50ppm	0.01ppm	-	N/A	-
Carbon Monoxide	Electrochemical	0 to 500ppm	1ppm	-	N/A	-
Formal-dehyde	Electro-chemical	0 to 5ppm	0.01ppm	-	N/A	-
Sound Pressure Level	Electret condenser microphone	-	-	-	N/A	-
Illuminance	Broadband photodiode	01 to 40,00 lx	0.1 lx	±3 lx	Konica T10A Konica minan Meter	0.99

3.3. SAMBA hubs

SAMBA's autonomous IEQ performance data acquisition and transmission does not require access to or cause disruption to any of the host building's existing services or information/communication networks. Data network autonomy was a design priority because of the extremely sensitive nature of many of the host buildings' data operations. As depicted in Figure 3, SAMBA's IEQ data stream is periodically transferred, using our own *ad hoc* wireless mesh network, back to a 'hub' that is centrally located within a building. A single hub is configured to service all SAMBA monitoring stations within each building. The hub collates time-series data from all nearby SAMBAs and transmits them through the public cellular telephone network to a remote server for quality assurance and subsequent assimilation into the IEQ Lab's cumulative database.

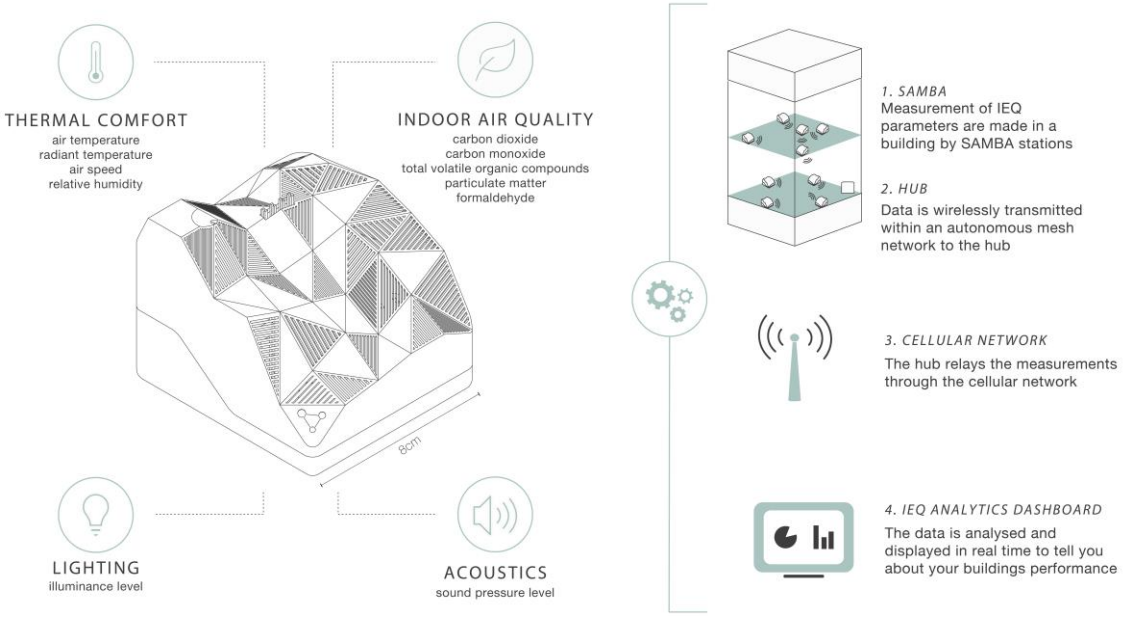

Figure 3: The SAMBA and IEQ Analytics concept diagram

3.4. IEQ analytics dashboard

Once on our server the SAMBA's data exports undergo some automated statistical analyses and visualization scripts for our on-line reporting procedures. The online portal, shown in Figure 4, has been specifically designed for interpretation by building facility managers (often non-technical personnel in Australia's commercial buildings sector), and delivers prompt and concise visualization of all measured IEQ parameters. All data are compared alongside the relevant IEQ standards and rating criteria (e.g. GreenStar "Performance" and NABERS "IE") to give building operators, owners and their tenants timely and intelligible reports on their building's IEQ performance. The IEQ Analytics portal was designed after extensive consultation and with a large sample (over two dozen) of industry stakeholders during three months of pilot testing in Sydney and Melbourne commercial office buildings.

Figure 4: The IEQ Analytics dashboard is a website that displays a building's real-time IEQ performance data (SAMBA data) in a format that is intelligible to, and useful for a building facility manager.

Apart from displaying measured parameters the dashboard also displays some derived comfort indices. For example, in the thermal comfort section of the dashboard is a real-time stream of PMV/PPD calculations (ASHRAE 2013). SAMBA collects all the requisite environmental parameters for PMV/PPD (air temperature, globe temperature, air speed and relative humidity). Once the data have been transmitted to the server, the first three parameters are used to calculate a mean radiant temperature. Apart from four environmental parameters PMV/PPD requires estimates of two so-called personal parameters, namely building occupants' metabolic rate and the intrinsic insulation value of the clothing ensembles being worn indoors. On the basis of extensive surveys in office buildings across Australia that have been collated together in the ASHRAE Global Thermal Comfort Database (de Dear, 1998) an estimate of 1.2 met units has been adopted in SAMBA's index calculations. Building occupant clothing insulation is estimated in real-time using ASHRAE Standard 55's statistical clothing model that is based on a running mean of outdoor air temperature, the latter being supplied by the closest automatic weather station and scraped from the internet by our servers on an hourly basis.

4. Research opportunities created by SAMBA

SAMBA provides a method for the efficient data acquisition of IEQ parameters en masse. Apart from providing timely and actionable IEQ data to building operators and facility managers, it opens up rich new possibilities for building science research. First and foremost SAMBA will feed the world's largest commercial building IEQ performance database. Such an extensive database of IEQ measurements will allow for a range of scientific investigations through data-mining, particularly when combined with subjective IEQ measurements from building occupants. For example, the database could be used to identify trends such as recently discussed "indoor climate change" – the observation that indoor summertime air conditioning temperatures have been drifting lower in Australia and North America, in

contrast to upward trends across most of Asia (de Dear, 2012). Exploration of the multimodal interaction effects of different IEQ vectors in commercial buildings would also be possible. This research topic is underdeveloped partly due to the methodological difficulties in collecting the appropriate data from the field. The research potential is not limited to commercial office buildings either – SAMBA affords the possibility of conducting investigations of IEQ in residential settings, health-care facilities, retail facilities, or educational institutions. SAMBA therefore marks a paradigm shift in indoor environmental quality research that will enable a range of interesting research avenues in the near future.

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