Development of a low-cost device for observing indoor particle levels associated with source activities in the home

Gustavo Olivares, Ian Longley, Guy Coulson
National Institute of Water & Atmospheric Research Ltd, Auckland, New Zealand

Corresponding email: g.olivares@niwa.co.nz

SUMMARY
A small instrument package was developed to continuously observe particles, carbon dioxide, temperature and movement at relatively low cost. Four identical packages were built and co-located in a test home alongside a wide range of more sophisticated instruments. The instruments were exposed to common indoor particle sources in a semi-controlled experiment, and during normal occupation of the house.
Results indicate that each sensor requires individual calibration. The responses of the CO2 and particle sensors were highly consistent and correlated with much more expensive instruments. The combination of CO2 and movement data was able to indicate the presence of persons in the room, although not unambiguously. Trials are ongoing to investigate the impact of instrument location within the home. The particle sensor responded clearly to cooking sources and the infiltration of outdoor particles on evenings with elevated ambient PM10.

KEYWORDS
Measurement technology, particulate matter

1 INTRODUCTION
Previous studies of domestic indoor air quality at high temporal resolution have indicated large, sudden increases in concentrations followed by more gradual concentration decays (e.g. Morawska et al., 2003, Bhangar et al., 2010, Longley & Gadd, 2011). These observations are consistent with relatively brief emission bursts from indoor sources followed by dilution due to internal air mixing, deposition and exchange with outdoor air. Individual indoor emission events can vary substantially in intensity and duration, and can dominate time-average concentrations over a typical day, or longer periods. Describing and accounting for variability in indoor concentrations between homes requires accounting for the variability in indoor source events. Documenting the implications of those concentrations for exposure, and ultimately health outcomes, requires the combination of source and concentration data with home occupancy data.

In many homes there can be a range of indoor sources of airborne particulates. Cooking activities have been shown to lead to substantially elevated indoor concentrations, even for brief activities, such as toasting (e.g. Wallace & Ott, 2011). However, other potential sources include indoor heating, candles, incense, evaporation from solvents, resuspended dust and pesticides. Chemical apportionment techniques can be used to indicate source contributions, but these often rely on time-integrated samples in which the temporal resolution required for exposure assessment is lost. The relative suddenness of concentration increases associated with emission bursts offers an alternative means of identifying those sources if the source activity can be observed with similar time resolution and accuracy. The simplest approach is to rely on diary techniques in which householders are asked to self-report source-related activities. With a high probability of error or omission, alternative approaches may include use of voice recording or video recording, although this is likely to lead to low levels of compliance in a ‘real world’ field study with volunteer householders due to perceived privacy concerns.

In a winter-time study of two volunteer homes in Christchurch, New Zealand in which home heating was provided using domestic woodburners (Longley & Gadd, 2011), we linked 1-minute resolution indoor PM_{10} observations with self-reporting diary records, logs of wood mass added to the burner and flue temperature to infer that the burner lighting and start-up process was responsible for most of the regular (1 – 3 times a day) observed large jumps in concentration. The association was subject to some uncertainty, however, consisting of some temporal discrepencies between events in the activity and concentration time series. Also, no records were kept in that study of cooking or other potential non-heating source activities and we cannot confirm that emission events we ascribed to woodburning were actually caused or confounded by cooking (or other) sources.

As an outcome of this study we concluded that in order to determine the role that heating, cooking and other sources were contributing to indoor particulate exposure, and how it may vary between homes developed an improved observational capability was required. We set out to develop that capability. Our objectives were

1. to measure PM at sufficiently high temporal resolution to delineate brief emission events, and at sufficiently low cost to be able to measure in a large number of homes.
2. to be able to observe, directly, or through proxies, the emission events themselves at a similar temporal resolution, and in a way that permits different source types to be distinguished.
3. to observe human occupancy for the purposes of exposure assessment.

This paper describes our design approach and process up to the point of building and testing four prototype instrument packages. It presents the results of an evaluation of the prototypes in a series of controlled tests.

2 MATERIALS/METHODS

Our agreed requirements for the instrument package were:

- low unit cost
- small form factor
- non-intrusive in the domestic environment

We also took the approach of designing around "open source" hardware and software in order to benefit from the global development community and therefore minimise replication and reduce the development time of this instrument. Late in 2010 we conducted a review of suitable low-cost components available and settled upon an initial design concept.

The key element was a ‘particulate dust sensor’. Due to its low cost and very small form factor, Sharp's Optical Dust Sensor (GP2Y1010AU0F) was chosen as the suspended particulate concentration sensor. In this sensor an infrared emitting diode and a phototransistor are diagonally arranged to allow it to detect the light scattered by dust in air. It is claimed to be especially effective in detecting very fine particles like cigarette smoke, and is commonly used in air purifier systems but because it doesn't include any sizing system, it is not possible to assess the cut-off size of its measurements and therefore will be refered hereon as PM. Complementing the dust sensor we elected to test the combination of an ultrasonic rangefinder and passive infra-red motion sensor to provide data from which relevant activities and room/home occupancy could be inferred. We chose to log the outputs of each sensor centrally at 1 second resolution to provide a single time-synchronised data stream that retains as much information as possible. The main micro controller is the ATMega328 based Arduino Pro Mini (http://arduino.cc/en/Main/ArduinoBoardProMini) with the Macetech's ChronoDot as the real-time clock. At this initial stage we chose to power the unit via mains although it remains our intention to allow alternative power sources in future versions to provide flexibility where mains power is not available or imposes limitations on the use of the units.

After initial tests verified the correct operation of this basic package, the National Semiconductor's LM335A analogue temperature sensor and Parallax carbon dioxide sensor were also added to provide further information from which occupancy, air exchange rates and combustion sources could potentially be inferred. All components were housed within a conventional electronics enclosure. The resulting package was named the **PACMAN**: Particles, Activity and Context Measurement Autonomous Node.

As indicated before, the PACMAN was designed within an open source hardware paradigm and as such the firmware is released under the LGPL and the design files under the Creative Commons Share-Alike license. The relevant files are available at the following repository: https://bitbucket.org/guolivar/pacman

The rest of this paper is concerned with evaluation tests conducted during 2011 at a 'Test House' in Auckland. This house is a normal property that the research team rented for the purposes of indoor air quality investigations. The house has intermittently been used as the normal residence of a research student, and this fact has been exploited for some of the tests described below. The student was fully aware of all tests and actively participated.

In Test 1, a short series of controlled tests were performed in the house aimed at testing specific questions around the PACMAN's performance. These consisted of

1.1 response to human movement at different distances
1.2 response to human movement at different angles of 'vision'
1.3 test for false positive data from rangefinder and motion sensor (pointing at blank wall and open window)
1.4 test for response of rangefinder and motion sensor to draught-driven curtain movement

In Test 2, the original unit was co-located in the lounge of the Test House whilst a duplicate unit was located outside of the house to capture ambient conditions. A large range of additional instrumentation was also installed and operated, including an optical aerosol sensor (TSI AM510 'Sidepak'). The instruments were systematically exposed to a range of common indoor emission sources following a 2-stage protocol. In stage 1 all windows and doors were closed and the emission was active for 10 minutes. In stage 2, the source was stopped and 30 minutes was allowed to elapse. In Stage 3 all external doors were opened and a fan operated to vent the indoor air for 10 minutes.

In Test 3, the original PACMAN unit was placed in the kitchen of the test house for a week in winter 2011. The unit was placed in a kitchen cupboard at adult head height with the cupboard door kept open. During the test the research student was the only occupant of the house. He was instructed to conduct his life normally, except for making experiment-relevant time-activity notes. As well as assessing general instrument performance, reliability and consistency, the general aim was to establish whether source-activities and occupancy patterns could be inferred from the PACMAN data.

3 RESULTS

Dust Sensor

When exposed to clean air (interior of air conditioned office, and at times within the Test House) the dust sensor was found to exhibit a baseline output voltage that was linearly proportional to temperature (measured inside the enclosure) over the full temperature range observed in all tests (18 to 28 °C). Thus the dust signal needs to be compensated for this effect. Figure 1 shows the temperature-corrected response of the PACMAN dust sensors and a Sidepak PM_{10} monitor to the controlled frying of olive oil during Test 3. The PACMAN baseline offset of ~1500 mV can be seen. A least squares fit to this data gives an R^2 of 0.99.

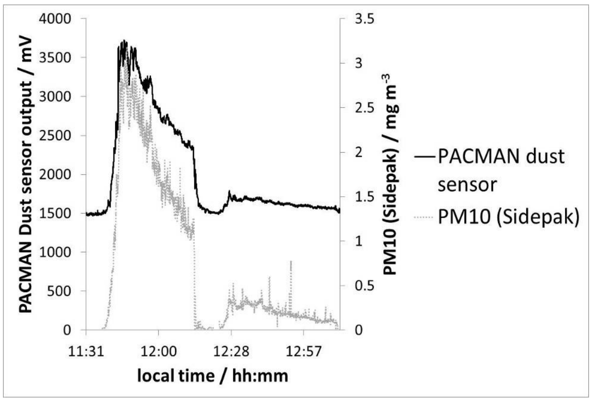


Figure 1: Response of PACMAN dust sensor and Sidepak aerosol monitor during a controlled test. The initial rise and plateau relates to the frying of olive oil. The decay follows the removal of the source. The rapid fall corresponds to the opening of doors and venting of the room.

Rangefinder

Test 1 revealed that the rangefinder was reliable in identifying a person standing, up to ~ 3m from the sensor. Beyond that distance the response became unstable – possibly due to reflections of the relatively wide beam from multiple surfaces producing an ambiguous noisy signal. We also found that the signal became unstable when the angle between the sensor's line of view and the target was greater than ~45 degrees. No errors were found when the PACMAN was pointed both at a blank wall, curtains or an open window. These results are likely to be specific to the particular rangefinder we used – many alternative sensors with different specifications regarding beam width are available.

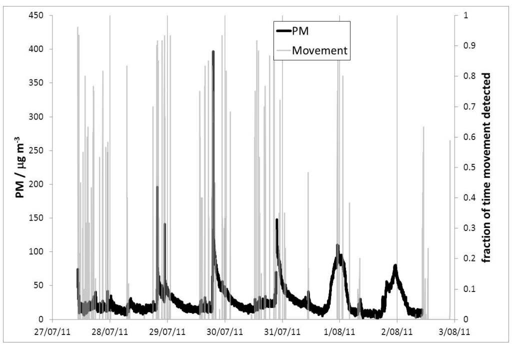
Motion Sensor

The motion sensor was generally very effective at detecting persons walking anywhere within the test room. In Test 1.1 we found that the sensor's ability to detect smaller movements (such as arm movements whilst stood still) deteriorated with distance from the sensor increased – for example, the sensor responded to small hand movements at ~ 1 m, but not at ~5 m. No false positives were reported when the PACMAN was pointed both at a blank wall, curtains or open window.

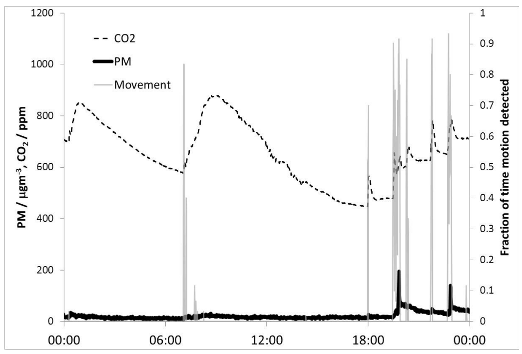
Test 3: Normally occupied house

The full time series from the PACMAN dust sensor during Test 3 (corrected for temperature and calibrated using the correlation with the Sidepak) averaged up to 1 minute resolution is shown in Figure 2. Also shown in grey is the fraction of each minute during which motion was detected. Although the occupant's time-activity records were relatively poor and incomplete, they were totally consistent with the motion records and CO_2 data. Five distinct PM peaks can readily be identified. Note, however that the purpose of the PACMAN is not just to identify these peaks, but provide contextual information to help identify their cause. The first three peaks have a distinctly different characteristic shape to the latter two. The former exhibit sudden peaks followed by smooth decays, similar to those observed in other studies and discussed in the introduction, corresponding to indoor emission events. The latter peaks exhibit a gradual increase followed by a slightly more rapid decay. Our motion data indicates the presence of a person in the home during the first three events, but not the latter two. This is corroborated by the CO_2 data (not shown). Figure 3 shows one of the days of Test 3 (28th July) in more detail. Increases in CO_2 are clearly associated with periods of movement being detected and vice versa. Two particle emission events are observed in the evening at times when motion was detected. Unfortunately, during this particular test, no meaningful data was extracted from the rangefinder. We suspect this was due to the positioning of the PACMAN on a cupboard shelf such that the rangefinder responded only to reflections from the cupboard door, rather than persons in the kitchen as was the intention. This means we were unable to corroborate whether the emission events were associated with kitchen-related activity. This is also the case with the other two indoor major events. Records from the student occupying the house revealed that the three inferred indoor events coincided with cooking activities. The second PM peak late on the evening of the 28th coincided with cigarette smoking. The more gradual rises in the dust signal on the last two evenings coincided with almost identical rises in outdoor PM (the same increases in CO_2 were also observed indoors and outdoors). This, together with the lack of recorded indoor motion, and low wind speeds and air temperatures recorded on these two winter evenings strongly imply that the source was external to the Test House and most likely due to the poor atmospheric dispersion of woodsmoke from domestic heating which commonly leads to elevated levels of ambient PM_{10} in Auckland in such conditions.

2a



2b



Figures 2a (left) and 2b (right): PACMAN dust sensor data (corrected for temperature and calibrated for PM_{10}), motion data and CO_2 (Fig. 2b only) from Test 3 (nornmally occupied house). Fig 2a (left) shows full data record for one week. Firg. 2b (right) shows one day only (28th July, day 2 of the experiment).

4 DISCUSSION

We set out to develop a low-cost instrumental package that could be deployed in occupied homes and from which indoor PM levels could be observed at high temporal resolution and for which additional, temporally-resolved contextual information could also be gathered from which emission sources and home occupancy could be inferred. At present we feel we have partly succeeded. The performance of the individual sensors, and their integration has been acceptable, with the dust sensor in particular providing data in excellent agreement with a far more expensive aerosol monitor, albeit for a limited and particular cooking source alone at present. The combination of dust sensor and motion sensor alone has been sufficient in these limited tests to identify the magnitude and timing of indoor emission events distinct from infiltration events, and confirm the presence of a single person in the home. The CO_2 and temperature data provided corroborating evidence. Our intention for the CO_2 data was to provide additional information about air exchange rates and the number of occupants, but this analysis has yet to be carried out. Identification of the source however (cooking, heating, etc) has not yet been achieved, mainly due to difficulties in using and interpreting the data from the rangefinder. Nevertheless, given the success of the design so far, we are confident that this can be overcome through a combination of either selecting alternative sensors, improved protocols for instrument use derived from better characterization, or gathering alternative source-specific data (e.g. appliance temperature).

5 CONCLUSIONS

A low-cost instrumental package to measure indoor particle concentrations and source-related contextual data was designed and has undergone some initial tests. The tests revealed that the dust sensor selected provided excellent agreement with a far more expensive aerosol monitor, albeit for a limited and particular cooking source alone at present. Whereas a motion sensor and CO_2 sensor successfully provided valuable data from which the presence of occupants could be inferred and indoor sources distinguished from outdoors, further development is required to be able to distinguish between sources (e.g. cooking, heating, etc.).

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6 REFERENCES

Bhangar, S, Mullen, NA, Hering, SV, Kreisberg, NM, Nazaroff, WW, 2010. Ultrafine particle concentrations and exposure in seven residences in northern California. *Indoor Air* 21, 132-144.

Longley, I.D., Gadd, J., 2011. High resolution PM10 measured inside wood-burning New Zealand homes. *Air Quality & Climate Change* 45(1), 21-26.

Morawska, L, He, C, Hitchins, J, Mengersen, K, Gilbert, G, 2003. Characteristics of particle number and mass concentrations in residential houses in Brisbane, Australia .*Atmospheric Environment* 37, 4195-4203.

Wallace, L, Ott, W, 2011. Personal exposure to ultrafine particles. *Journal of Exposure Science & Environmental Epidemiology* 21, 20-30.