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**Article**

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## Research paper

## Active fume hood sash height monitoring with audible feedback

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## HIGHLIGHTS

- Chemical fume hoods are responsible for a majority of wasted energy in many labs.
- Closing a fume hood sash when it is not in use reduces the amount of energy wasted.
- We show that audible reminders to close fume hoods when not in use save energy.
- The platform developed here can quantify behavioral modification in many applications.

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## ABSTRACT

Fume hoods in laboratories consume the energy equivalent of up to four American households per hood; however, closing a modern hood's sash completely can save up to 75% of that energy. Past efforts have attempted to harness this potential energy reduction by reminding users to close the sash when a hood is not in use. In this work, we developed a device to measure the efficacy of these energy-saving methods. The device records the position of the sash and detects motion to determine whether a user is present, and, when fitted with a piezoelectric buzzer, can *audibly* alert users to close the sash when not in use. We installed this device in laboratories to quantify the energy and cost savings resulting from real-time audible feedback and found that the alarm reduced wasted energy by 87 to 98%. In addition, the platform demonstrated here can be used to quantitatively test other energy-saving methods that rely on user behavioral change in future work.

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## 1. Introduction

Working with hazardous gases, vapors, or aerosols puts a laboratory user at risk for their health and safety. The fume hood was designed to provide an enclosed space for using these hazardous materials in a controlled environment, with air flow into an exhaust system as a form of user protection. Aside from the exhaust system to contain the fumes, hoods also contain sliding glass sashes which shield the user from splashes or fires when performing experiments in the hood. The ventilation provided by fume hoods requires high air exchange rates, drawing air from the heating, ventilation, and air conditioning (HVAC) systems of the building in which they reside, and rejecting the conditioned air to the outdoors. The energy required for this draw on the HVAC system

can account for over 60% of the energy used in laboratories (Weale et al., 2002). Depending on the type of fume hood, merely closing the sash when the hood is not in use can result in power savings of up to 75% (Weale et al., 2002).

Two main designs constitute the majority of all fume hoods. Constant air volume (CAV) hoods operate at a constant air exchange rate regardless of the hood sash position. CAV hoods consume approximately the same amount of energy regardless of the sash height. Alternatively, variable air volume (VAV) hoods alter the air exchange rate based on sash position, allowing for energy savings when the sash is lowered. All chemical fume hoods are required to maintain a minimum face velocity, which is the airflow velocity through the open area of the hood beneath the sash, to ensure the safety of users (Tseng et al., 2010; U. of Massachusetts, 2006). VAV hoods use sensors to measure the change in sash height and adjust the airflow accordingly to maintain face velocity (Deluga, 2000; National Research Council (US), 2011); each VAV hood consumes an amount of energy proportional to the height of its sash (Gilly, 2015; MIT, 2017; Gevelber et al., 2014; Reed, 1994; Taylor, 2004). In comparison to CAV hoods, VAV hoods are more

Abbreviations: VAV, Variable air volume; CAV, Constant air volume; HVAC, Heating, ventilation, and air conditioning; AR, augmented reality; OpenCV, Open computer vision; FPGA, Field programmable gate arrays

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energy efficient, as their built-in closed feedback loop reduces unnecessary wasted energy (Feustel et al., 2015; Macdonald, 2016). The energy costs of VAV hoods are 40%–60% of the energy costs of CAV hoods (Deluga, 2000). This study investigates how to further reduce wasted energy consumed by the already-more-efficient VAV fume hoods. Of the approximately 750,000 fume hoods across the United States, the percentage VAV hoods is roughly 67%; therefore, this work highlights a significant opportunity to save energy (Gilly, 2015; MIT, 2017; Gevelber et al., 2014; Reed, 1994; Taylor, 2004).

To understand how to save energy consumed by fume hoods, prior work has focused on measuring fume hood energy consumption (Parker, 2006). From a building management perspective, the overall energy required for ventilation connected to multiple hoods can often be obtained directly. However, it can be difficult to measure the total energy being used by one individual fume hood. A simple and more direct way to measure the amount of energy used by an individual fume hood is by measuring the position of the hood sash over time. By measuring sash height, the rate of air volume that is drawn into the hood can be determined. To maintain a proper airflow for the safety of the fume hood user, the face velocity (linear speed of air flowing into the opened sash) must be kept at a predetermined value. Using the face velocity, sash position, and other fume hood specifications, the energy consumption can be calculated for an individual fume hood.

Many studies have been conducted in efforts to increase energy savings from fume hoods by closing the sash. While some studies investigated fume hood use practices specifically, most studies tested user feedback by using visual reminders or by providing incentives for those who keep their sash closed most frequently when the hood is not in use (Feder et al., 2012; Woolliams et al., 2005; Amanti, 2006; Mills, 2009). In 2005, Harvard University started a campaign called “Shut the Sash” and conducted a study to determine whether user feedback would result in significant hood energy savings; they found that hoods with automated sash closers and sash stickers combined yielded 70% energy savings and approximately \$200,000–\$250,000 in utility savings based on building-level data (Gilly, 2015; Posner et al., 2011). University of California Davis and University of California Santa Barbara conducted similar studies using only sash stickers in 2012 that resulted in a savings of \$1,300 per hood annually (Bell, 2012). In 2007, rather than using a visual reminder, Caltech summer research students tested user feedback in efforts to close sashes using a pizza party as an incentive that resulted in a change from sashes being closed 9% of the time to 76% of the time and, correspondingly, savings of \$3,412 per hood annually (Hilliard, 2008). At MIT in 2010, Wesolowski, et al., tested user feedback to close hood sashes by displaying a graph of how often the hood was open in monthly reports, reducing the average sash height by 26% and saving \$41,500 per year throughout the chemistry department at MIT. Wesolowski, et al., along with authors of other behavioral modification studies, noted that feedback seems to be most effective when delivered as close as possible to the time of the action (Wesolowski et al., 2010; Hovell and Hughes, 2009; Euliano et al., 1999). This concept influenced our idea to use real-time audible feedback to alert users to close their hoods when they are not in use. There are many advantages and disadvantages to using audible feedback with users. Future improvements for this form of feedback could include analyzing the best way to implement the audible feedback, such as the type of alarm and how long it sounds, among other design aspects, as these concepts have been extensively analyzed in past studies involving alarms and human responses (Bellettiere et al., 2014; Wilcox, 2011).

In the present work, we developed a device to (i) log energy consumption data for an individual fume hood, and (ii) remind lab users to close the fume hood sash when it was left open and

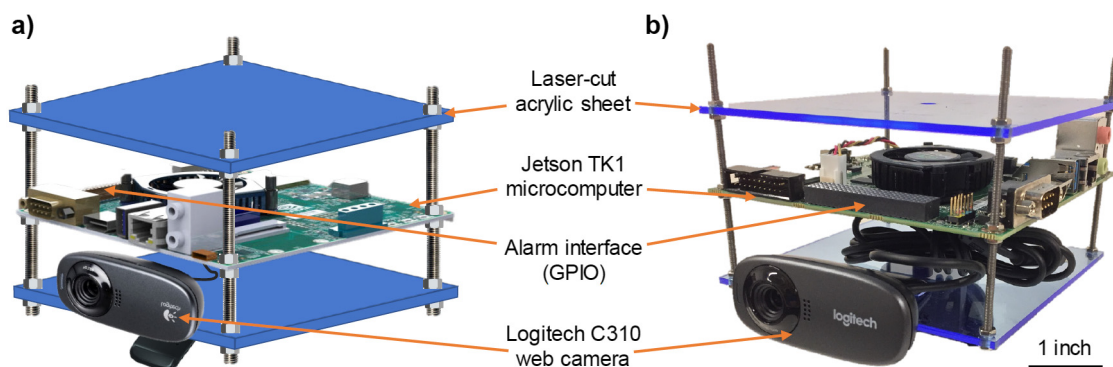
not in use. By reminding users to close the sash when not in use, the average sash height was decreased, resulting in lower average airflow drawn through the hood and, correspondingly, less energy consumption. This device is comprised of a microcomputer, video camera, and alarm, shown in Fig. 1. Interestingly, we note that prior studies have found that user behavior can be influenced by environmental surveillance (Meleady et al., 2017; Bateson et al., 2006). The video camera on the device was visible to lab users, and its influence on behavioral changes resulting in better fume hood sash closure practices may play a role in the results obtained here.

We wrote a program which takes input from the video camera and measures the sash position at a given sampling rate by viewing augmented reality (AR) tags on the hood. We also used the video camera to detect whether the hood is being used via a motion detection algorithm. Based on both of these metrics, we were able to determine the amount of energy wasted when a fume hood was left open while not in use, allowing quantitative exploration of energy-saving behavioral-modification methods at the scale of a single fume hood. To test the capability of this device, we attached an alarm to the microcomputer which was activated when a hood was left open and not in use for a specified period of time, with the goal of determining whether audibly alerting users would significantly reduce the amount of time the sash was open when the hood was not in use, therefore reducing the amount of wasted energy consumed by the hood. At a price point of under \$265, and with a projected annual savings of about \$360 based on our experiments, these devices will pay themselves off in a period of about 15 months, representing a promising solution for a significant reduction in energy wasted by fume hoods.

## 2. Methods

To record the sash position over a period of time, we designed an embedded system with a microcomputer (NVIDIA Jetson TK1) and video camera (Logitech C310). To incorporate feedback and test our device's capability to quantitatively measure behavioral change, we connected a small piezoelectric alarm to the microcomputer which sounded when the sash was detected to be open without a user present within the last 45 seconds. The Jetson microcomputer is encased in laser-cut 5" × 5" acrylic sheets on the top and bottom, held together by threaded rods and steel hex nuts (Fig. 1). The casing also has a slot to hold and position the video camera at an angle capable of capturing the entire fume hood in the camera frame. Additionally, we used an attachable flexible tripod to place and position the device in lab spaces with less practical installation space, for example, by attaching the device to overhead pipes or ductwork by wrapping the legs of the tripod around these fixtures (see Appendix A). This device was used to visually monitor fume hoods with a video camera using motion detection and AR tag detection, store the status of the fume hood sash height and user presence at the hood, and, in the case of the behavioral change test, trigger an alarm when a hood was wasting energy (i.e., when the sash was open and the hood was not in use).

Using Open Computer Vision (OpenCV), we wrote a program in Python to detect AR tags (Fig. 2(a)) and measure the distance between the tags, which were placed above, below, and on the hood sash. We used the OpenCV module Aruco to find the distance between the tags and wrote an algorithm to store the position of the sash. The Aruco module contains a reference library of AR tags which were used to recognize any tags in the video frame regardless of size, angle, or rotation of the tags from the camera perspective. The program also incorporated a motion detection algorithm to record the last time a person was detected at the hood as viewed by the video camera. The program collected and recorded the data at five-second intervals. For more detail on the code, see Appendix B.



**Fig. 1.** Fume hood monitoring device. A schematic of the fume hood monitoring device is shown in (a) with the main components labeled. The Jetson TK1 microcomputer is held between two laser-cut acrylic sheets via four pieces of threaded rod and steel hex nuts. The video camera is positioned on the device through a slot on the bottom acrylic sheet. A photo of the actual fume hood monitoring device is shown in (b) with a 1-inch scale bar.

To convert sash height into energy, we accounted for several values unique to each monitored fume hood. Each fume hood has a face velocity, which is a measure of how fast the air is pulled into the open sash, typically recorded in feet per minute (fpm). Face velocity can be different for every hood, and it is set based on the hood size, design, and type of work it will be used for (Meisenzahl, 2017). Given the face velocity and position of the hood sash, we determined the overall volumetric flow rate at which air enters through the open hood sash in cubic feet per minute (CFM). This rate is linearly dependent on the sash height and can be used to calculate the power drawn from an individual hood at the time of sash position measurement (Ekberg and Melin, 2000). To determine the power consumption of a hood, we multiplied the air volume rate in CFM by a conversion factor calculated from the input power of both the supply fan and the exhaust fan. The standard value for this conversion factor for most chemical fume hoods is 1.80 W/CFM, which is the value used in this study (Weale et al., 2002). With the power draw data recorded for each time step, we numerically integrated over time to calculate the energy consumed by the hood.

After we recorded the data for sash height and user motion, we calculated how much energy was being wasted during the monitoring time period. Wasted energy is defined as the amount of excess energy consumed by the fume hood due to the sash being left open when the fume hood is not in use, indicated by no motion detection for a period of longer than 45 seconds.

### 3. Experiment

To determine whether the audible feedback had a significant impact on influencing users to close the fume hood sash, we conducted two experiments at each hood studied: a control experiment, in which the alarm was disabled but usage data (i.e., sash height and presence of lab users) was still recorded, and a subsequent test experiment, in which the alarm was activated while also recording usage data. We conducted two sets of experiments: one set at MIT during the summer, and one set at the University of San Diego (USD) during the winter and spring. The first set of experiments, at MIT, was conducted over the course of two weeks (one week for the control and one week for the test), and the control and test were conducted on the same hoods, sequentially. We conducted all of our experiments on VAV hoods because the energy savings expected with CAV hoods are negligible using this approach. We installed a total of four devices at fume hoods in MIT labs within the Departments of Chemical Engineering, Materials Science and Engineering, and Mechanical Engineering. After the control portion of the experiment, we activated the audible feedback system in the form of an alarm to begin the test portion of the experiment. The second set of experiments, at USD, was conducted

over the course of six weeks. The first three weeks were in the fall semester (control) and the second three weeks were in the spring semester (test). For this set of experiments, the device was installed in an organic chemistry lab. At the conclusion of all of the experiments, we collected and analyzed the data recorded by the devices. The devices stored the date and time, sash height, motion detection status, and alarm status at the time of each measurement (every 5 seconds).

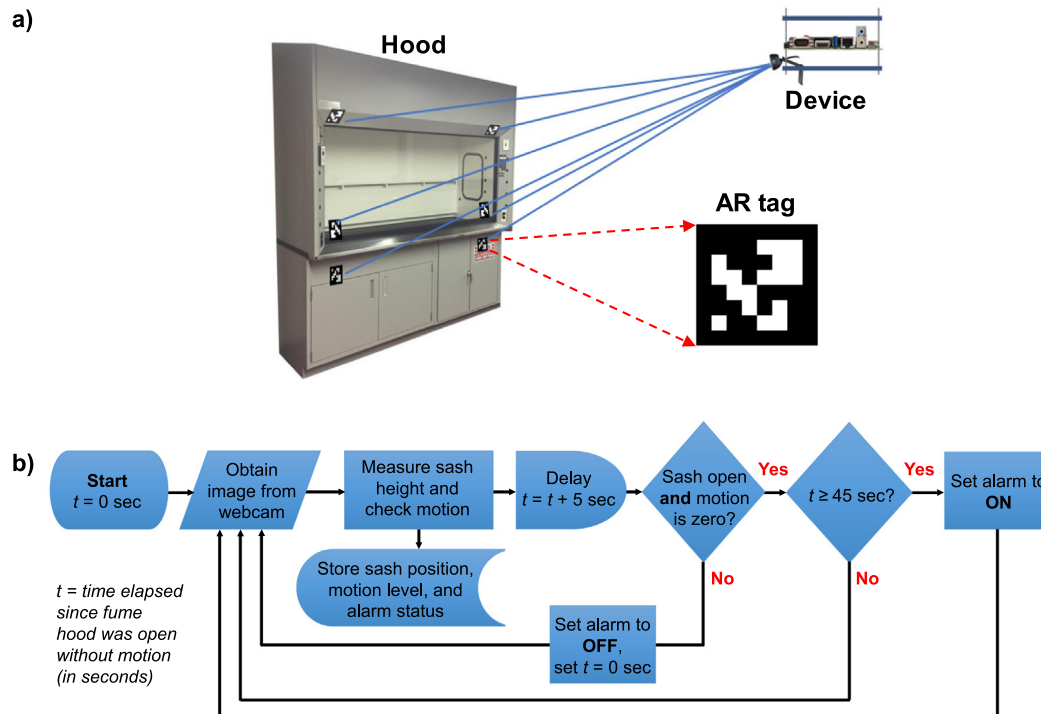
Prior to running each experiment, we calibrated the height threshold used to determine whether the sash was considered “open” or “closed” for the purpose of deciding whether to initiate audible feedback. To do this, we ran the program with the AR tags attached to the hood and moved the sash to a position 1 inch above the point at which the sash could be closed no further. This sash height level left a margin of error to avoid the alarm activating when the sash appeared to be closed to lab users. We followed this procedure for every installation in the experiment, as the video camera position in reference to the AR tags varied from hood to hood. Although this procedure added an extra step to the installation process, it allowed for accurate determination of sash height.

We also tuned the motion detection threshold to avoid false alarms. Considering that fume hood users can remain relatively still while performing experiments which require careful precision and focus, the threshold needed to be low enough to detect even slight user movements. In addition, we set the inactivity time required before alarming to 45 seconds, considering that users sometimes need to step away from the hood for a short amount of time (perhaps to retrieve a forgotten item); we decided that it would be unreasonable to sound the alarm in these cases.

Another factor to consider during setup of the device is the placement of the AR tags. We laminated a majority of the AR tags to be used in the experiments to avoid water damage. However, during installation we found that some of the tags were not being detected. During troubleshooting, we learned that some of the tags were not being detected due to a glare from the reflection of both indoor lighting and outdoor sunlight on the lamination material. To solve this issue, we replaced those laminated tags with tags that were not laminated and the issue was resolved. For future experiments and long term installation, it would be beneficial to laminate the tags with a different material that is less reflective but still protects the tags.

The issue with reflections also arose during the choice of method for detecting motion in the code. Frame subtraction (comparing a captured frame to the previous captured frame) can result in false positives, which would occur when the algorithm thinks there is motion from a user when it is actually from another source, such as a reflection of movement elsewhere in the lab on the hood





**Fig. 2.** Setup and monitoring device. (a) The illustrated fume hood setup demonstrates detection by the video camera onboard the fume hood monitoring device. Augmented reality (AR) tags placed on the fume hood allow the device to detect the sash position, as shown. The setup shown here, with the device elevated relative to the fume hood, exemplifies the flexibility of the camera perspective when viewing the AR tags. (b) The logic used to implement the alarm on the monitoring device is presented as a flow chart. The alarm sounds when the fume hood sash is open *and* there is no motion for at least 45 seconds. Once movement occurs or the sash is closed, the alarm turns off.

sash glass, or the reflection of a tree moving outside a window. An alternative algorithm to detect motion could use additional AR tags along the bottom of the hood. Motion would be detected when any of those bottom tags are not observed in the frame, meaning that a user is covering one of the tags. However, this method also has several drawbacks. One issue is the possibility that something else could block the tag, such as an inanimate object placed in front of the hood. Another issue is the possibility that a tag would be removed from the hood. These scenarios would result in false positives of motion detection and would significantly affect the data collected and the triggering of the audible feedback. With this in mind, we used frame subtraction, taking care to avoid spurious motion due to reflections by choosing appropriate camera angles.

Once the data files for both the control and test portions were collected for each of the hoods studied in this experiment, we analyzed the data to quantify changes in user behavior. We calculated how often and for how long the fume hoods were left open and not in use for both the control and the test period and compared these findings to draw conclusions about the effectiveness of audible feedback as an energy-saving behavioral-modification strategy.

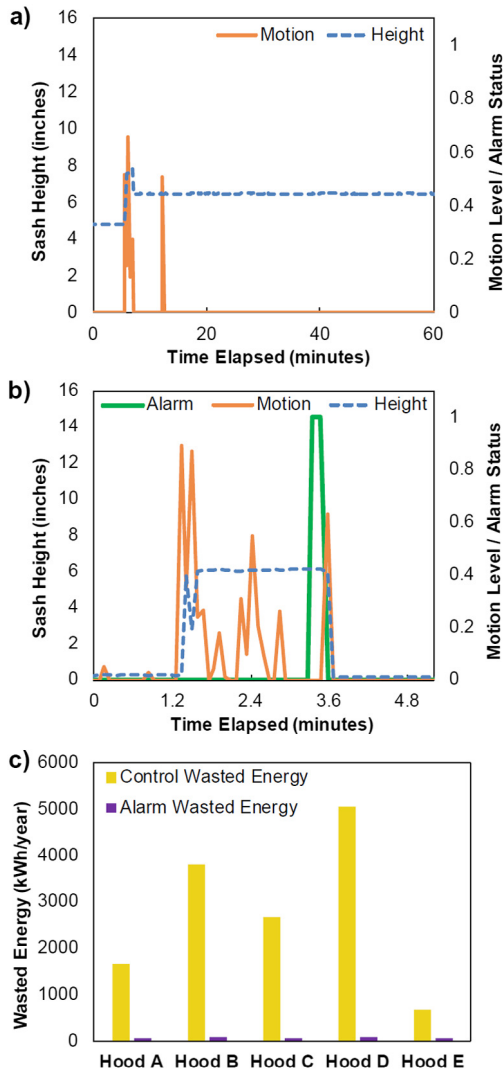
#### 4. Results and discussion

The results of the study showed changes in user behavior regarding fume hood practices and a corresponding reduction in wasted energy. The overall average sash height was reduced by 79.2%, an improvement compared to the 26% reduction in the previous study at MIT by Wesolowski et al. (2010). The most accurate way to compare the resulting energy savings from this study to those of previous studies is through relative measures like percent reduction in average sash position, rather than absolute energy or monetary saving values. This is primarily due to disparities in the amount of time a fume hood is in use, but also due to the absolute number of fume hoods considered and the models and efficiencies

of various designs. Some fume hoods are used more consistently than others. At USD, the hoods are used less often than at MIT, because the USD labs are purely undergraduate research labs and are generally not used as frequently as the graduate-level research labs at MIT.

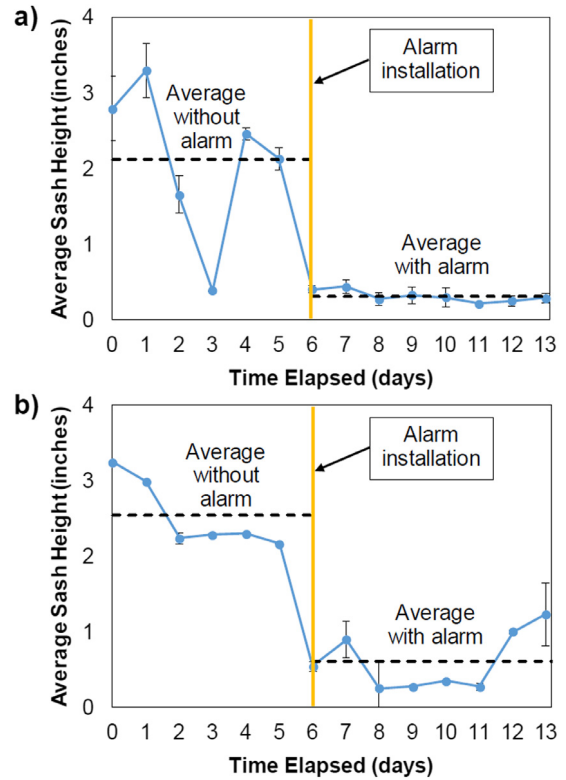
The overall average time the hood was open was reduced by 96.6% after the alarm was implemented. For example, prior to the activation of the alarm, one of the hoods was open for a total of 140.6 h (5.9 days) during the week of the control experiment, primarily without users present. After the audible feedback system was activated, the amount of time the sash was open decreased to 4.9 h (0.2 days) during the week of the test experiment. Furthermore, the hood was in use (motion detected) for 3.6 out of the 4.9 h of the hood being open, meaning that the hood was in use for 73% of the time that it was open when audible feedback was used. Another hood was open for 46.6 h (1.9 days) per week before the alarm was activated; this was reduced to 1.3 h (0.05 days) per week when audible feedback was used. For this hood, it was in use for 0.93 h of the 1.3 h of the hood being open, yielding a use percentage of 72% for the time that it was open. The other 29% of the time that the hood was open was primarily the duration of time it took for users to hear the alarm and return to close the hood sash. These numbers alone exemplify the drastic change in fume hood practices with the audible feedback reminder.

In the control experiment data, there were consistent trends illustrating poor practices of fume hood use resulting in unnecessarily wasted energy. For example, there were several nights during which hoods were left open and not closed again until after the next time of use the following day. This never occurred during the test portion of the experiment when the alarm was implemented. The experimental data during the test period illustrates the immediate closing of the hood sashes once the alarm began to sound. An example of the changes in fume hood use practices is shown in Fig. 3. The graph in Fig. 3a shows a sample of data



**Fig. 3.** Reduction of wasted energy. The plot in (a) illustrates a sample of data before the alarm on the fume hood monitor was activated, during the control experiment. The sash height (blue line) increased when there was indication of use (user motion, light orange line) for a few minutes. After there was no longer motion in the frame, meaning the hood was no longer in use, the sash remained open for an hour, during which time the hood was wasting energy. The plot in (b) illustrates a sample of data for the *same* hood after the alarm was implemented on the device. This plot shows motion when the hood sash was opened. After a few minutes, when there was no motion for at least 45 s, the alarm was triggered (green line), causing the user to return to the hood and close the sash before leaving. The chart in (c) summarizes the comparison of wasted energy before and after the alarm was implemented on the hoods tested in this study, which ranged from 87%–98%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

without the alarm implemented on the device when a user left the fume hood open for an hour, wasting energy. Fig. 3b illustrates the behavior change of a user at the same hood, where the user closed the sash after the alarm was triggered by the user leaving the open hood for at least 45 seconds (alarm status of 0/1 corresponding to off/on is indicated by the green line). Additionally, the user left the frame of the video camera after returning to close the hood, suggesting that they had no intention of continuing to use the hood when they had initially left. These patterns were consistent throughout the data for all of the hoods tested in the experiment, and are prime examples of the behavior change observed as a result of audible feedback from the device. The change in user behavior was also documented by the change in average daily sash



**Fig. 4.** Average daily sash heights. The plots in (a) and (b) illustrate the average daily sash heights for fume hoods A and C, respectively. The average daily sash heights before the alarm was installed are shown initially during the control portion of the study, and the average daily sash heights with audible feedback (alarm installed) are shown to the right of the vertical line indicating alarm installation. The average daily sash heights after the alarm was installed were reduced by nearly 2 inches in both cases. Error bars represent the 95% confidence interval of the mean.

height before and after audible feedback was implemented, shown in Fig. 4. The average daily sash height decreased by, on average, nearly 2 inches for both of the fume hoods (hoods A and C) plotted in Fig. 4, enabling an alternative approach to interpret the results of this work.

We compared the resulting wasted energy values for each fume hood (control and test) for the tested hoods and calculated the corresponding savings in both energy and energy bill costs (see Table 1). The monitoring device itself draws approximately 61.3 kWh/year of energy. We compensated for this power draw by subtracting it from the reduction in wasted energy. Additionally, we calculated the amount of time it would take to pay off the initial cost of the device, which cost approximately \$264.34 (see Appendix C, Table C.1) (Preston and Woodbury, 2013). We divided this value by the savings in monetary costs for each tested fume hood to determine the payback period (see Table 1).

When returning to the labs to check on the devices and collect data, several lab users commented on their experiences with the alarm. One lab user noted that a labmate left a fume hood open and walked away for longer than 45 seconds, causing the alarm to sound. However, the labmate had headphones in their ears, leaving them unable to hear the alarm, and therefore they did not close the hood. Eventually, other lab members noticed the alarm and closed the hood after notifying their labmate that the alarm was on. This observation in the study led to the idea of possibly adding another element to the audible feedback, such as a flashing light for cases where the user cannot hear the alarm. While this factor highlighted potential faults in the audible feedback method, it exemplified how the hood sash was still closed earlier than it would have been had the device not been installed, thanks to other lab members.

**Table 1**

Reduction in wasted energy. This table shows the amount of projected energy wasted annually for the control experiments (no alarm implemented), the corresponding projected energy wasted annually for the tests with audible feedback, and the difference between the two values. The corresponding annual cost savings in energy bills (with an energy cost of \$0.1327 per kilowatt hour) and the resulting payback period of the device based on the cost savings for each hood were calculated.

Hood	Control wasted energy (kWh/year)	Alarm wasted energy (Including device power) (kWh/year)	Reduction in wasted energy (kWh/year)	Cost savings (\$/year)	Payback period (months)
A	1662.05	69.99	1592.06	211.27	15.0
B	3812.01	78.88	3733.13	495.39	6.4
C	2678.30	64.93	2613.37	346.79	9.1
D	5048.33	99.36	4948.97	656.73	4.8
E	672.34	88.20	584.14	77.52	40.9
Average	<b>2774.61</b>	<b>80.27</b>	<b>2694.33</b>	<b>357.54</b>	<b>15.2</b>

Several lab users from another lab in which we installed the device commented that they caught themselves habitually closing the hood sash after the alarm was implemented for a day or two. This is promising user feedback, as it exemplifies the routinized behavioral change in fume hood practices we sought in the motivation of this study (Gardner, 2018). Future studies with the audible feedback method can be conducted to test how effectively this behavioral change is instilled in the fume hood users, even after audible feedback is removed. The results from such a study could potentially provide more evidence for the efficacy of real-time audible feedback compared to other forms of feedback that may suffer from “banner blindness” (Gilly, 2015; Bell, 2012).

It is important to note that the tested hoods for this study also had sash stickers similar to those used in the previous fume hood energy studies at UC Davis and UC Santa Barbara in efforts to encourage closing the fume hood when it is no longer in use (Bell, 2012). We were still able to reduce the wasted energy by at least 87%, even with the visual feedback method used in previous studies already implemented. This trend in data also shows the impact of immediate feedback after the time of action and how the persistent audible reminder can encourage better fume hood practices. Perhaps most importantly, it is an empirical representation of why this energy saving method is more effective than those of past studies.

This device was used to demonstrate that audible feedback is more effective than other types of feedback used in the past (visual, incentivized, etc.) (Ho et al., 2008). If a device that uses audible feedback were to be commercialized and installed in other laboratories outside of MIT and USD, it could be further simplified and reduced significantly in cost. Future work at MIT will focus on developing a device using only a magnetic limit switch, an infrared motion detector, and a piezo alarm controlled by an Arduino UNO. These changes not only simplify the installation and setup of the device, but also cut down the price and reduce the payback period of the device significantly, while eliminating privacy concerns related to the video camera and the need to record or store any data. With this outlook in mind, we found that the device presented in this study is a useful platform to quantitatively characterize the efficacy of energy-saving behavioral-modification methods, exemplified by its use here to provide the proof that audible feedback works. Future work will compare the results obtained with the device designed in this study to the results obtained with the simplified device described above for verification that the audible

alarm system is equally effective without video monitoring. This future work will also guide which methods should be implemented on a larger scale.

As shown, an effective way to achieve long-term energy savings is by changing everyday behavioral practices. For laboratories, this includes altering equipment use practices, as well as selection of more energy efficient equipment. Modifying behaviors of lab users usually entails some type of incentivization, as we saw in this work and in previous studies. However, the energy saving methods will not be effective unless the form of feedback is consistent and difficult to ignore with time, such as an alarm. Other lab behaviors and practices that can be modified with the feedback device used in this study include turning off lights when there is no motion for a certain threshold period (if motion sensors are not already installed) or limiting the time that a piece of lab bench equipment can be powered on after not being used for a threshold period. The device used in this study has the ability to offer the same impact on other lab behaviors as it did for fume hood use practices here.

## 5. Conclusions

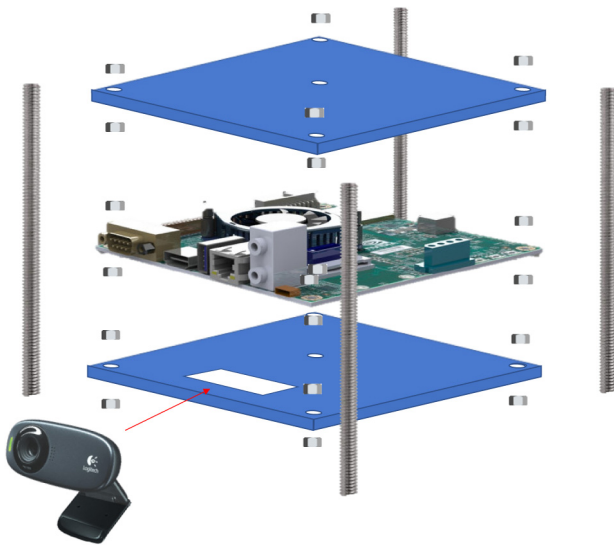
These results demonstrate the energy-saving impact of real-time audible feedback to alert fume hood users when the sash is open while a hood is not in use. With a payback period of just over a year, this proposed method of reducing wasted energy can be easily implemented at any VAV fume hood to generate a net financial gain. Furthermore, based on the quantitative evidence demonstrated here, a less sophisticated and more cost-effective version based on simpler sensors and processors, and without the need for data logging, is a feasible future step with a clear path to broad adoption and commercialization. Finally, because the unique monitoring characteristics of the device are based on open-source image processing software (e.g., AR tags and OpenCV), this device can be used as a test platform not just for behavioral modification methods at fume hoods, but also for applications in area lighting, water use, waste streams, and beyond.

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## Author contributions

All authors contributed to conception of the idea. L.B., J.F., M.D., A.S.A., and D.J.P. developed the working device. L.B., J.F., and M.D. performed the experimental analysis. E.N.W. and D.J.P. guided the work.



**Fig. A.1.** Fume hood monitoring device before assembly. The disassembled device is shown with the hardware components surrounding the Jetson TK1 microcomputer. These components consist of 24 steel hex nuts, four 3"-long steel threaded rods, two 5" × 5" acrylic sheets, and the Logitech C310 web camera. The acrylic sheets contain each contain four laser-cut holes for the threaded rod inserts and a center hole for the attachment of the flexible tripod. The video camera is positioned on the device via a laser-cut opening indicated by the red arrow in the figure.

## Appendix A

### Device fabrication

The most time-consuming aspect of creating this device was initially writing code for the microcomputer. The remaining manufacturing tasks to build this device are a matter of physical assembly of components. Fig. A.1 illustrates the device components prior to assembly.

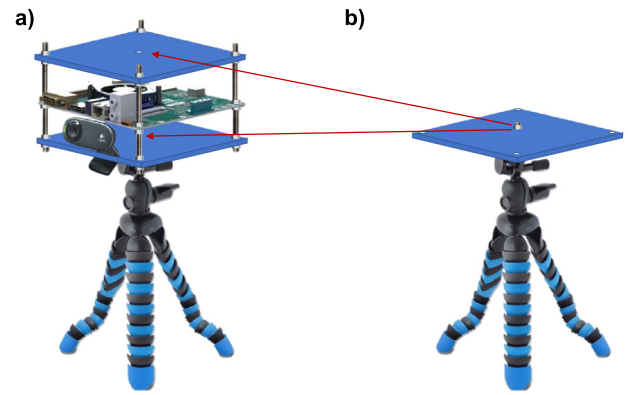
Fig. A.2 illustrates the full assembly of the monitoring device with the attached flexible tripod. This illustration is a model of what the actual device looks like before installation in a lab. A hole was cut into the top and bottom cases to allow for attachment of the tripod, making it easier to install in laboratories with minimal available space.

## Appendix B

### Code description

The algorithm for the monitoring device was written in Python using Open Computer Vision (Open CV) modules to detect the AR tags and sound the alarm when the hood was detected to be open and not in use. The program was split into three different sections for the purposes of organization and ease of understanding the code.

The main program has manual inputs that are specific to the apparatus setup and preferences of the user. Motion detection threshold will vary depending on how sensitive the user wants the motion detector to be. The recording length is altered if the user wants to run the program for a different amount of time. To run the program indefinitely, which is what we used for running the program for longer than a day, this value should be -1. The sash height threshold is set based on what value the user wants the hood to be considered "closed". The logic of the main program consists of checking both (i) if the sash is open (taken from the sash height



**Fig. A.2.** Flexible tripod application on fume hood monitor. (a) The fully assembled fume hood monitoring device mounted on the flexible tripod is illustrated. The tripod is used to position/place the device in a variety of places in laboratories with minimal available space. (b) The tripod attaches to the acrylic case via a center-cut hole and is secured by tightening a steel hex nut onto the small threaded rod insert. The red arrows indicate the two possible placements of the tripod on the device. The tripod can either be attached to the top of the device to hang the device from above, or to the bottom of the device to configure it in a standing position.

calculation program), and (ii) if the hood is inactive (taken from the motion detection program), and triggering the alarm if these conditions are satisfied. It also indicates the values stored in the csv file at the end of every checking point.

Open CV has extra modules that can be used for special features/functions within the programs. The module used in this program is called the Aruco module. This module allowed for the generation of AR tags from an already existing Aruco library, the detection of the tags, the calibration of the web camera, and various other functions that can be done with AR tags. For the purposes of this project, we utilized the module's ability to generate and detect the AR tags. We developed the rest of the algorithm to measure the sash height after detecting the tags. When the module detects the tags, it returns the "coordinates" of the corners of the tags, as well as the ID of the tag that it is given from the original library. We decided to ignore the tag IDs, as we felt it would be simpler to not have to worry about printing the correct tags and placing them in a specific spot on the hood. The algorithm used to measure sash height uses the returned coordinates after tag detection and finds the rightmost tags and leftmost tags. Since there are three tags on each side (one on the top of the hood, one on the sash, and one on the bottom of the hood), we used these vertical differences to calculate a ratio. During post-analysis processing, we multiply this ratio by the actual measured distance during the installation to get the measurement of sash height opening.

To calculate sash height, we only needed to put tags on one side of the hood. We decided to put tags on both the right and left side of the hood as a precautionary measure in case someone or something blocks one of the tags. Once the left and right side sash heights are calculated, we return the actual sash height as the maximum of those two values. If no tags are detected (perhaps meaning that the lights are off and it is night time), the sash height program will return a -1. In the data analysis, we assume the last recorded sash height value before returning a -1 is the same sash height that would be recorded if the lights were on.

The motion detection subroutine utilizes frame subtraction to determine if there has been motion in the frame. Frame subtraction is the capture of multiple consecutive frames for a specified period of time (in this program it runs for three seconds) and each frame is subtracted from the previous frame to check if there has been a significant difference in pixels seen by the web camera. The threshold value, set in the main program, can be altered depending



**Table C.1**

Monitoring device cost breakdown. Each component of the monitoring device is listed along with its corresponding price. The device totals to approximately \$264.34, however, it is important to note that many of these prices can be reduced if the components are purchased in larger bulks.

Component	Cost (\$)
NVIDIA Jetson TK1 microcomputer	200.00
Logitech C310 web camera	32.00
Flexible tripod	14.99
SD memory card (32 GB)	12.99
Encasing	2.50
Threaded rod	0.42
Hex nuts	1.44
<b>Total</b>	<b>264.34</b>

on how sensitive the user would like the motion detector to be. To decrease the sensitivity of the detection, the threshold value for what is considered a significant change in frame should be increased and vice versa for the opposite. Altogether, these three sections create a working algorithm for sounding the alarm when the hood is open and not in use based on specifications decided by the program/device user.

## Appendix C

### Financial analysis

The commercial components of the device (microcomputer, web camera, tripod, and SD card) were purchased online at the prices specified in Table C.1. The other material costs listed (acrylic encasing, threaded rod, and hex nuts) were determined from the calculations below:

$5'' \times 5''$  acrylic sheets (ordered from McMaster-Carr)

•  $0.125'' \times 12'' \times 12''$  acrylic sheet = \$7.84

$$\frac{\$7.84}{12'' \times 12''} \cong \$0.05/\text{inch}^2$$

$\$0.05/\text{inch}^2 \times (5'' \times 5'' \text{ acrylic sheet}) \times 2 \text{ sheets} = \underline{\$2.50 \text{ total}}$

Steel threaded rod (ordered from McMaster-Carr)

• M3  $\times$  0.5 mm thread size, 1 m long = \$1.40

$\$1.40/\text{m} \times 0.075 \text{ m rod} \times 4 \text{ rods} = \underline{\$0.42 \text{ total}}$

Steel hex nuts (ordered from McMaster-Carr)

• 18–8 stainless steel hex nut M3  $\times$  0.5 mm thread, pack of 100 = \$5.55

$$\frac{\$5.55}{100 \text{ nuts}} \cong \$0.06/\text{nut}$$

$\$0.06/\text{nut} \times 24 \text{ nuts} = \underline{\$1.44 \text{ total}}$ .

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