Design and Assembly of an Inexpensive Cleanroom for CubeSat Teams

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ABSTRACT

As space missions become more accessible to student teams through the spread of the CubeSat standard, there is an obvious desire for inexpensive clean spaces for satellite assembly. However, commercially available cleanrooms are costly and may not fit in limited spaces. We present our results and processes from the design, construction and testing of a low-cost cleanroom made of materials readily available at hardware stores.

Our cleanroom was designed to meet ISO 8 or better standards, based on results from previous work by other groups (Johnstone et al., 2007)[1] and requirements for our CubeSat missions. Overall, $2,733.51 CAD was invested into the materials for the cleanroom. The cost was reasonable for the budget of a typical university student group developing critical CubeSat infrastructure.

Particle count testing was conducted using a PurpleAir PA-II air quality sensor for continuous monitoring of the cleanroom performance. Particle counts recorded over three months suggest that the cleanroom can meet ISO 8 requirements and further operate under ISO 7 cleanroom conditions[2] most of the time. Particle counts occasionally spiked above the ISO 7 threshold for periods of up to three hours.

INTRODUCTION

AlbertaSat is a student-led space technology group from the University of Alberta currently working on three CubeSats as part of the Canadian CubeSat Project. For this mission, AlbertaSat was in need of an efficient and reliable cleanroom for final assembly, however none were readily available in the University. Since most commercially available cleanrooms are too costly, AlbertaSat decided to construct a portable and inexpensive cleanroom that would satisfy ISO 8 cleanroom specifications. This document outlines the background and design process of a 4.3 x 4.3 x 2.4 m cleanroom. Previous designs such as that in *Fabrication of an inexpensive cleanroom module for microsystem testing* from the Institute for Micromachine and Microfabrication Research (Johnstone et al., 2007)[1] inspired the design. The cleanroom was constructed using 2 industrial-grade air filtration units, schedule 40 ABS pipes, and vinyl sheets among other items.

DESIGN OVERVIEW

The cleanroom design features a rigid frame consisting of common plumbing supplies. 1.5-in schedule 40 ABS pipes are used along with PVC tee and elbow joints to create a frame that stands approximately 2.3 m tall, covering a 4.3 m x 4.3 m area. Using the same materials, a central column covering an area of 0.75 m x 0.75 m supports two industrial air filtration units overhead as shown in Figure 1 and Figure 2. Pipe segment lengths can be shown in Figure 1 and symmetry can be assumed aside from the door. All vertical pipes are cut to the same length.

Vinyl is used on the walls and ceiling and fastened with sheathing tape. A door is created using overlapping vinyl strips hanging from the roof to allow easy entry and exit.

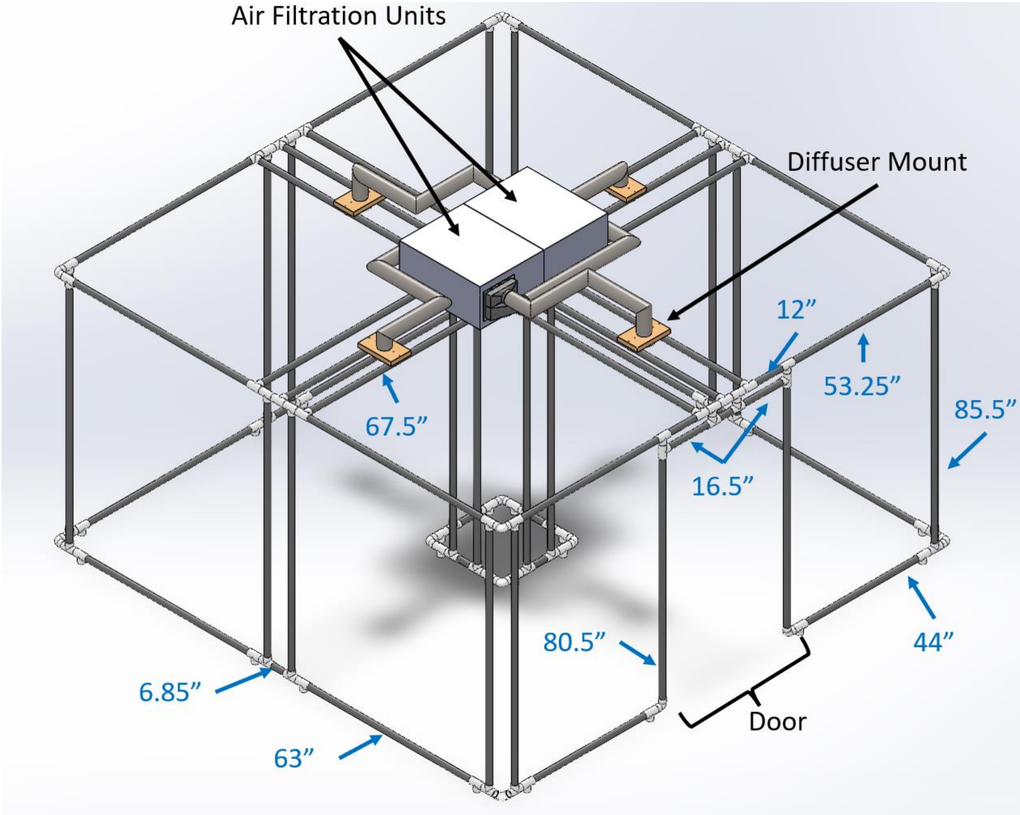

Figure 1: A CAD Model of the Cleanroom Frame

The air filtration units intake air from the surrounding laboratory space, with a 1 micron inner filter and a 5 micron outer filter. The units discharge the clean outlet air into two paths, each going to a different diffuser within the space. From here, cleaned air enters the cleanroom through diffusers mounted to PVC trim boards attached to the upper frame.

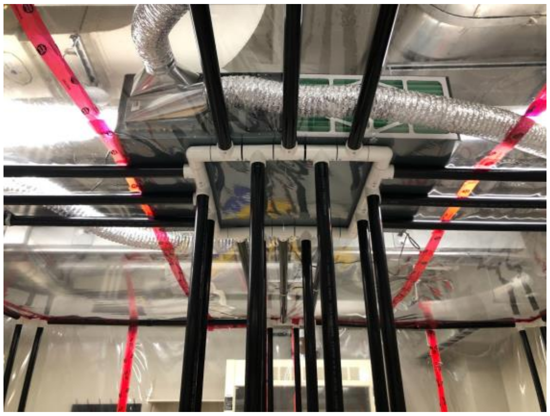

Figure 2: Air Filtration Units Draw Filtered Air From an External Laboratory Space

An intermediate “grey room”, shown in Figure 3, was constructed at the entrance of the cleanroom using scrap ABS piping tied to overhead equipment within the laboratory space. This space is used to hold additional supplies and PPE that would be required before entering the cleanroom.

Figure 3: An Intermediate Space Between the Unfiltered Laboratory Space and the Cleanroom Door

ASSEMBLY AND CONSTRUCTION PROCESS

Tools and Materials

In the hope that others may wish to replicate the design described above, the required tools and materials will be discussed in detail in this section. The bill of materials for the cleanroom structure is shown below in Table 1. While the cost may vary by location, AlbertaSat constructed the cleanroom for a total material cost of $2,733.51 CAD.

Table 1: A Bill of Materials for Assembly

Part name	Quantity
1-1/2-in Sch. 40 ABS pipe (12 ft/pipe)	45
PVC T-Joints (1 1/2-in)	105
PVC Elbow Joints (1 1/2-in)	22
Air Diffusers (4-in)	4
Air filtration unit (KAC-1200 ex)	2
Trim Boards (3/4 in)	1
Round Washer Head Screws (8x1-in)	2
Corrugated Plastic Sheet (2.5-ft x 3-ft x 3.99-mil)	2
Tuck Tape (60mm x 66m)	7
Sanding Sheets (9-in x 11-in)	2
PurpleAir PA-II Air Quality Sensor	1
MERV-13 Panel Air Filters	2
Vinyl (4 1/2 ft x 45 ft clear 16 mil)	4
Dryer Transition Duct (4-in)	3
Straight Duct Boot (4x10x4-in)	2
End Duct Boot (4x10x4-in)	2
Metal Gear Clamp (4-in)	6
Ratchet Straps	1

Assembly Procedure

After acquiring all of the necessary materials, the pipes were cut to the prescribed length, and the excess pieces were saved as joint connections (primarily where one T joint/elbow joint would directly connect to another joint with no piping in between). In total, the design used 40 pipes, each 12 ft long. To attach the aluminum ductwork to the air filtration units, an acrylic mount was made to provide a surface for securing duct boots to the air filtration unit outlet.

All pipes were deburred to allow for smoother joint connections. Following the CAD model in Figure 1, a rigid frame of ABS pipe interlocking with PVC fittings was constructed. All connections were fastened with screws to provide rigidity.

Next, vinyl sheets were added as the walls. Vinyl sheets were cut and attached onto the frame with tuck tape. The width of the vinyl was 40 inches as governed by the width of the roll. The vinyl was cut to approximately 90-inch strips so that it could be comfortably taped to the roof and floor pipes. After attaching all wall pieces, the roof sheets were made. Three sheets were needed for the roof, each around 127 inches long to cover the entire length of the roof.

Lastly, holes were cut in the vinyl where diffusers were to be added. PVC trim boards were screwed to the overhead pipes to mount diffusers and other ductwork The filters, combined with the duct boots mounted to its side, were then placed on top of the central support column. The ductwork was then complete upon connecting the duct boots to the diffusers using flexible dryer transition duct. To secure the filtration units, ratchet straps were wrapped around the roof beams.

SUPPORTING ANALYSIS

Load Calculations

The weight of both air filtration units generate an axial load on the vertical ABS pipes that form the central support column. To ensure the overhead air filtration units are safely supported, a buckling calculation for the vertical ABS pipes within the support structure was conducted. Due to the placement of the air filtration units, the combined weight of both air filtration units was assumed to be evenly distributed throughout the central support column. This would allow for the use of Euler's formula to predict the critical axial stress:

$$\sigma_{cr} = \frac{\pi^2 E}{(KL/r)^2} \tag{1}$$

Where σ_{cr} is the maximum stress in the column before buckling, E is the modulus of elasticity for ABS, L is the length of the pipe and r is the radius of gyration. The pipes were treated as fixed at both ends, with an effective-length factor (K) of 0.5[3]. Pipes were interpreted to be fixed at each end given that the top frame constrains translational motion of the central support column from the top, and the 8 total pipes are joined in a manner that also prevents rotation. Due to the predominant downward force acting on the structure, the possibility of the central support column moving from the bottom was deemed highly unlikely and treated as a fixed connection with respect to the ground. For a single pipe in the column, the calculated critical stress was found to be 1.13 MPa. The modulus of elasticity for ABS was taken as 1380 MPa as per ASTM standards[4].

The applied stress was calculated as follows:

$$\sigma = \frac{P}{A} \quad (2)$$

Where P is the applied force due to the air filtration units and A is the cross-sectional area of the pipe. Continuing with the assumption of an evenly distributed load among the 8 pipes, the stress experienced by each pipe was calculated to be 0.11 MPa. This is significantly lower than the previously calculated critical stress.

Air Exchange Rate (AER)

In an attempt to surpass the internal ISO 8 cleanroom requirement, the target air exchange rate (AER) was 1.7 exchanges per minute to comply with ISO 7 cleanroom standards[2]. The AER of this cleanroom design was verified using equation 3 below.

$$AER = \frac{f}{V} \quad (3)$$

Where f is the flow rate in m^3 /min and V is the volume in m^3. The volume was calculated to be 42.5 m^3. Assuming that when the cleanroom is in use, the air filtration units are at the highest setting, the calculated *AER* was 1.72 exchanges per minute.

Computational Fluid Dynamics Study

The nature of the airflow within a cleanroom is critical to its ability to remain free of contaminants. Typically, air is intended to travel from the ceiling diffusers to be exhausted out of the clean space without major recirculation. Without furnishings to the cleanroom, one could conclude that the airflow within the space would be able to accomplish this, however the effects of furnishing the space to be functional for AlbertaSat's mission are unclear without further analysis.

In order to qualitatively determine the effects of adding furniture to the airflow within the cleanroom, a preliminary computational fluid dynamics (CFD) study was performed using ANSYS CFX. This preliminary analysis is only intended to provide insight into the flow regime within the furnished space, without needing to investigate specific details of the flow. As a result, the CFD study conducted in this report has not undergone a formal grid independence analysis and further, more accurate simulations are ongoing.

To begin, a simplified model of the cleanroom was created in Figure 4 complete with desks, a laminar flow table, and AlbertaSat's Thermal Vacuum Chamber (TVAC). This model was then discretized using 510438 nodes to generate the mesh as shown in Figure 5. From here boundary conditions were implemented as prescribed normal velocities at the diffuser outlets, as measured using anemometers; and atmospheric pressure at the ground outlets. The application of boundary conditions can be visualized in Figure 6.

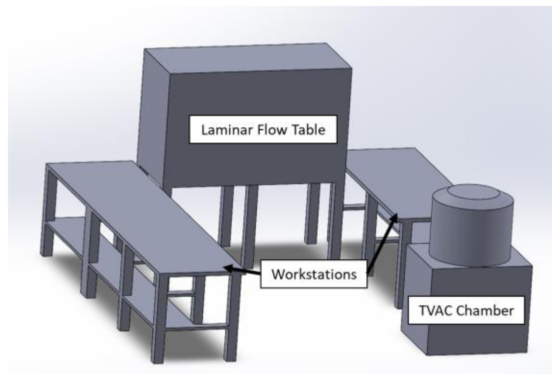

Figure 4: A Simplified Model of Furnishings Within AlbertaSat's Cleanroom Space

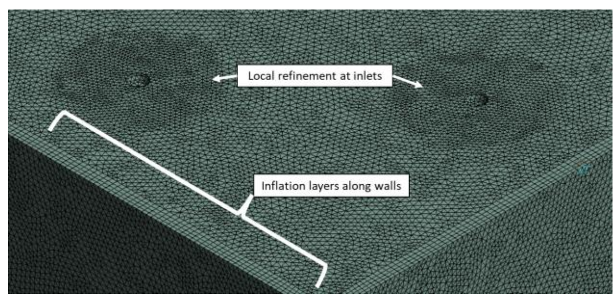

Figure 5: The Mesh Used for the CFD Study

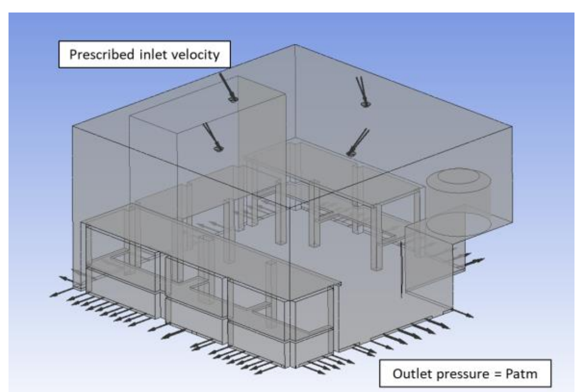

Figure 6: CFD Model With Boundary Conditions Applied

The model was then solved using the following solver controls shown in Table 2:

Table 2: A Summary of CFD Solver Settings Used

Setting	Value
Analysis Type	Steady State
Inlet normal velocity	356.75 ft/s
Outlet average static pressure	0 kpa
Advection Scheme	High resolution
Residual type	RMS
Residual target	1.00E-04

By observing the results of the above model, one could determine that there appears to be significant regions of recirculation on the tabletops given the large vortices revealed in Figure 7. It is expected that placing furniture within the space will introduce disruptions to the flow, however as the results in Figure 7 suggest, placing furnishings against the cleanroom walls may hinder overall performance. AlbertaSat is currently investigating alternative ways to include all necessary furnishings for late-stage satellite integration, testing, and assembly without compromising cleanroom performance through heavy recirculation zones. If possible, furniture placement should be done away from the soft walls to allow the internal air to flow over objects without recirculation.

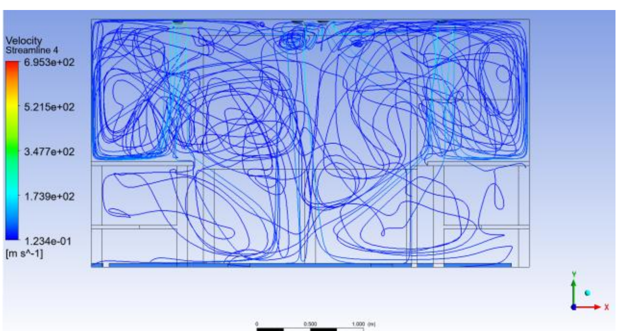

Figure 7: Preliminary CFD Results Showing Large Recirculation Above Desks

TESTING OVERVIEW

Particle Counting

In order to continuously monitor the particle, count in the cleanroom, AlbertaSat employed a consumer air quality sensor, the PurpleAir PA-II. This sensor uses a dual laser particle counter and allows for real time data monitoring. ISO 8 and ISO 7 compliance requires that particle counts for contaminates larger than 0.5 µm, 1.0 µm, and 5.0 µm are limited to the value specified by the respective standard. To summarize, ISO 8 and ISO 7 compliancy is governed by upper limits on contaminant particle concentrations as shown Table 3.

Table 3: ISO Limits for Relevant Particle Counts[2]

Particle Concentration (particles/dL)		Standard	
		ISO 8	ISO 7
Particle Size	Larger than 0.5 µm	352	35.2
	Larger than 1.0 µm	83.2	8.32
	Larger than 5.0 µm	29.3	2.93

RESULTS AND DISCUSSION

AlbertaSat has been utilizing its low-cost cleanroom extensively as of February 1, 2022, with little problems during operation. A sample of particle count measurements taken by the PurpleAir PA-II sensor over a 3-month period can be shown for particles of > 0.5 µm and > 1 µm with respect to their ISO 7 threshold in Figure 8 (a) and (b), respectively. Particles of size > 5 µm were never recorded by the PurpleAir sensor as the sensor consistently displayed a zero-particle count.

Taken together, the low-cost cleanroom is able to meet the particle count requirements of an ISO 7 cleanroom for the majority of operational time. At times, particles larger than 0.5 µm appear to spike within the space bringing the recorded concentration above the ISO 7 threshold of 35.2 particles > 0.5 µm / dl. Observing other PurpleAir sensors in the nearby area online does not show an obvious correlation to indicate Edmonton weather effects. While the cause of occasional spikes in particle counts of 0.5 µm is still unknown, one explanation for such fluctuation can be attributed to the design of the PurpleAir PA-II sensor. Typical cleanroom particle counters actively intake air through an internal vacuum system before particles travel across the laser particle counter. In the case of the PurpleAir sensor, there is no apparatus put in place to ensure sufficient airflow over the laser particle counter. This leaves the opportunity for lighter particles to remain circulating through the particle counter laser for an extended period of time, thereby registering select particles multiple times.

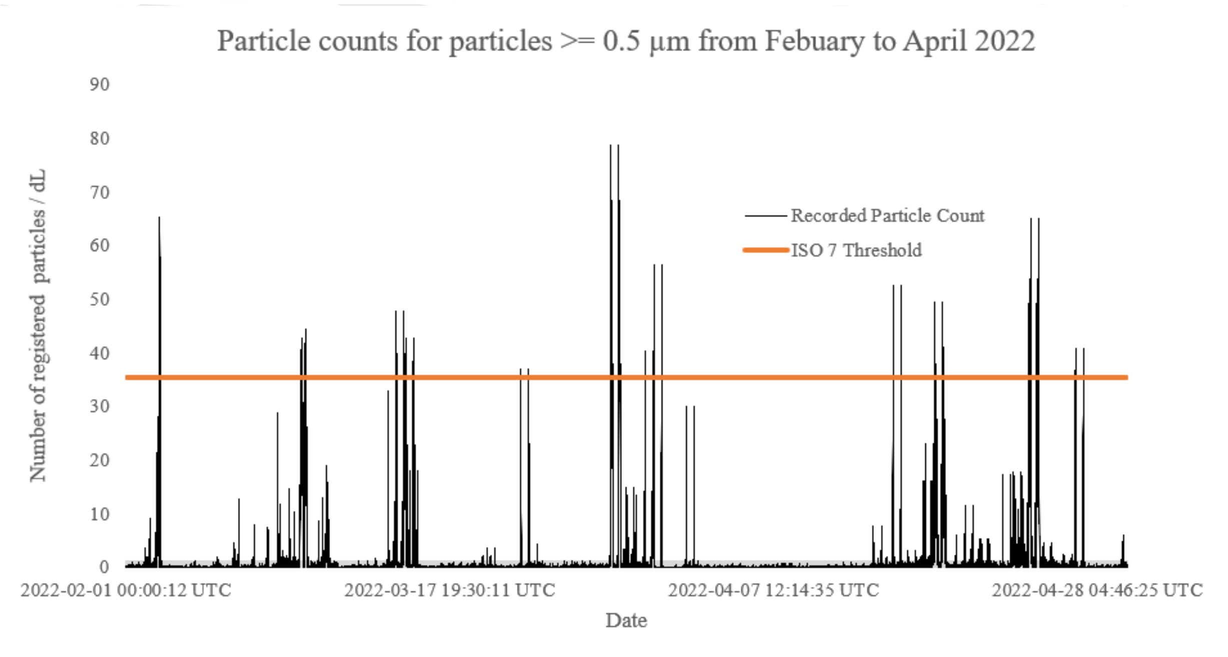

Figure 8 (a): PurpleAir Particle Counts For Particles Larger Than 0.5 µm Over a Three-Month Period

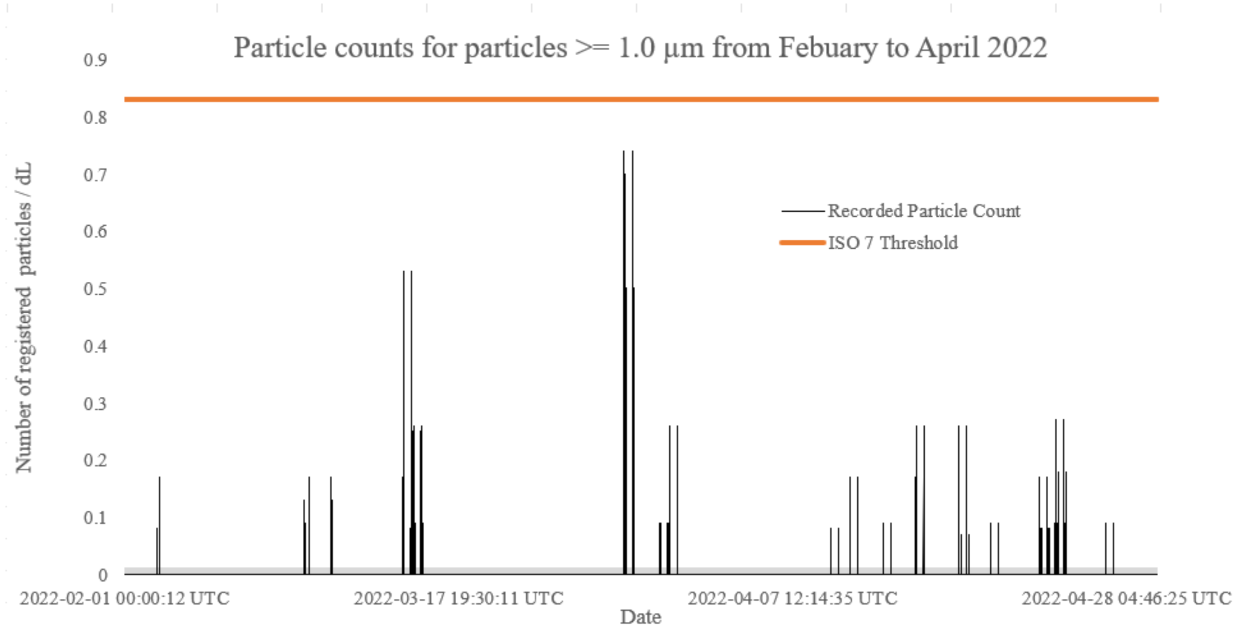

Figure 8 (b): PurpleAir Particle Counts For Particles Larger Than 1.0 µm Over a Three-Month Period

The CFD analysis conducted in previous sections may support this claim, given that the PurpleAir sensor is placed in an isolated corner of the cleanroom. This leaves the particle counter in the midst of a slow-moving recirculation zone as shown in Figure 9. While results are preliminary, the flow regime indicated by the early-stage CFD study indicates that the airflow carries little momentum in the identified recirculation zones. This leads to the possibility of lighter particles remaining trapped in vortices around the particle counter laser, however more extensive simulation will likely be needed to provide a definitive explanation.

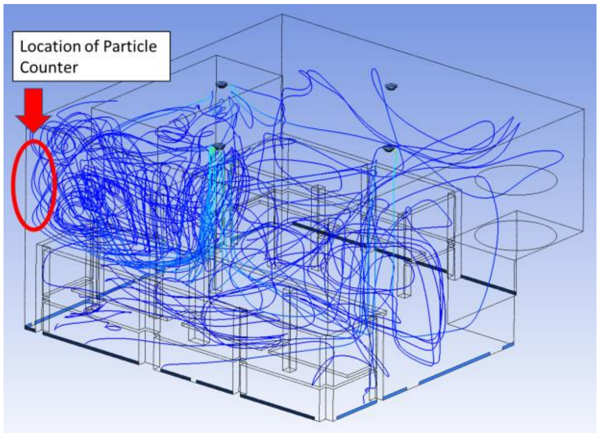

Figure 9: PurpleAir Sensor is Mounted in a Corner Subject to High Recirculation

LIMITATIONS

While the cleanroom is able to consistently meet AlbertaSat's operational requirements the design is not without limitations, many of which become a matter of convenience and functionality. The space itself is limited and further constraints arise when considering the effect of furnishings on the cleanroom flow regime. In the event that any maintenance needs to be done on the continually operating overhead air filtration units, one would need to cut a hole in the vinyl ceiling for appropriate access. This ultimately implies that the simple task of replacing filters after long term use would require a complete shut down of any operations within the space considering contamination concerns.

As for functional limitations, the cleanroom can operate at ISO 7 for the majority of the time, however this is insufficient to consider the design a true ISO 7 cleanroom. When the cleanroom does not satisfy ISO 7 operational requirements it is not often correlated to other increases in contaminate particles within the surrounding area. To mitigate spikes in measured contaminate particles, AlbertaSat has experimented with various filters. The foam filters that come standard with industrial air filter systems were found to be insufficient and current results displayed above showcase the cleanroom's performance using MERV 13 filters. Upon changing filters, it proved beneficial to seal any gaps, using spare tuck tape, along the edges of the air filtration unit and filter interface to prevent dirty air bypassing filters. It is expected that upon utilizing cleanroom grade filters, such as HEPA filters or similar, results may improve.

CONCLUSION

With the growing need of an inexpensive cleanroom to develop critical CubeSat infrastructure, AlertaSat has taken it upon themselves to design and construct an inexpensive cleanroom to function up to a minimum of ISO 8 standards. The design is consistently able to meet such standards and further adheres to ISO 7 cleanroom specifications in terms of volumetric air exchange rate, and particle counts for the majority of operational time. Due to the proposed layout of furnishings within the space, the cleanroom displays a high degree of recirculation in the flow regime above workstations. This is a detriment to overall cleanroom performance and allows for contaminate particles to stay within the space for prolonged periods of time instead of immediately expelling outside the space. Regardless, the cleanroom continues to function under AlbertaSat's internal requirements for a reasonable cost of approximately $2700 CAD in materials.

REFERENCES

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