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Novel Multipurpose Air Purification and Distribution Robot with AI-Based Anomaly Detection

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ABSTRACT: Maintaining optimal indoor air quality (IAQ), humidity, and household safety are critical to improving overall health. Poor IAQ and improper humidity have adverse health effects. To a limited extent, stationary air purifiers and humidifiers address these issues. I experimented with multiple humidities and air quality sensors placed throughout a room, which showed that a standalone air purifier or humidifier could not distribute air evenly within the space. I solved the uneven distribution and household safety with an innovative robot containing an air purifier, humidifier/ dehumidifier, Ultraviolet C (UVC) lamp (disinfects air by killing most bacteria and viruses such as COVID-19), cameras, and microphones. My custom-built robot uses a Jetson Nano, LiDAR, cameras, microphones, and air quality and humidity sensors. The robot and the air handling system were modeled in Computer-Aided Design (CAD), analyzed with Computational Fluid Dynamics (CFD) to find various components' optimal design, and built with 3D printed parts. AI-based environmental anomaly detection uses the microphone to detect unusual events, such as a glass breaking, smoke alarm, etc., and a camera for human fall detection. The robot was programmed using the Robot Operating System (ROS) to navigate a mapped room to avoid obstacles or until it detects poor air conditions or household safety anomalies. A LiDAR sensor, visual odometry, and an AI-based object detection algorithm accomplish navigation and obstacle detection. My experiment shows that the robot can humidify and purify the air in a room more evenly than standalone devices and detect environmental anomalies.

KEYWORDS: Robotics and Intelligent machines; Air quality; robot; distribution; Environmental anomaly detection.

Introduction

Poor indoor air quality (IAQ) increases heart rate, discomforts such as headaches and sleeplessness (insomnia), eye irritation, and illnesses like asthma.[1-3] Low humidity causes dehydration and dryness and leads to an increased chance of eczema and infection due to virus survival.[4] Dry air irritates the airways, leads to worse sleep, and affects asthma, among others. Low humidity also causes damage to wood furniture and hardwood floors.

An improvement of 10 parts per million (PPM) of Particulate Matter (PM) 2.5 in the air led to a life expectancy of up to 22 months longer for people aged 30 years.[5] Reductions in air pollution accounted for as much as 15% of the increase in life expectancy.[6] In addition, better air quality has been related to improvements in overall health aspects, including child lung growth, reduced chance of asthma, and lowered heart rate.[7]

Air purifiers with High-Efficiency Particulate Air (HEPA) and Carbon filters are effective.[8] HEPA filters are proven to help reduce the pollutants in the air by trapping the particles. Typically, the HEPA filters trap pollen, pet dander, dust, micro-organisms, and allergens such as mold and tobacco smoke.[9] The activated carbon filter removes smells, Volatile Organic Compounds (VOC), gases, fumes, and chemicals. The combined use of both filters leads to cleaner air and even better sleep.

Air circulation is vital for keeping air cleaner everywhere. However, not all places are created equal, so air circulation may not be even. As a result, some parts of an occupied room may not have the same air quality as others. Therefore, air distribution is critical to have improved air quality in a room.[10]

Humidifiers increase humidity in a room to keep the range between 40% and 60% for people's comfort. Humidity outside of this range can affect people's physical and emotional well-being. The two major types of humidifiers are evaporation-based and ultrasonic-based. Ultrasonic humidifiers add humidity by breaking up the water into tiny droplets. Evaporation humidifiers humidify the air by evaporation from a sponge. Optimal moisture helps to maintain the health of the people in a room.

Higher humidity content is also a problem, as too much humidity can cause people to feel hot and drive mold growth. A dehumidifier removes humidity from the air and converts it to water, which can be drained.

COVID-19 and other bacteria and viruses threaten many people in schools, homes, hospitals, etc. Ultraviolet -C (UVC) LEDs deactivate and disinfect these microbes.

Additionally, many households have medical accidents or intruder break-ins that injure or kill occupants. Microphones and cameras can monitor and detect potential hazards to notify people of dangers. The house is one of the most used buildings, and its safety is essential. In addition, many injuries happen to elders, and security can help provide peace of mind for them and their well-wishers.

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Therefore, improving IAQ, maintaining humidity at a certain level, removing bacteria and viruses, and detecting household anomalies, such as break-ins and fall detection, are essential for healthy and safe living.

The current development is to resolve all the above issues mentioned. This was done through the creation of a smart novel robot using AI and machine learning that can:

- Purify the air and remove pollutants
- Disinfect the air to remove viruses and bacteria
- Humidify or dehumidify the air
- Detect environmental audio and video anomalies to protect residents
- Perform all these tasks in a smart robot that can distribute air evenly and navigate between rooms

Some air purifiers are bigger than others. Small ones (about 1.5'x0.5'x2') are not particularly good for cleaning the air of a big room because they are not powerful enough. In these instances, periodically moving the small air purifier is required to clean the air in a large room. Even though the larger air purifiers (about 2'x1'x2') are better for larger spaces, they cannot clean the air in every part of the room. This is due to poor airflow caused by a lack of air circulation and stagnant air in a few pockets of the room. One solution is to use multiple air purifiers. However, they would occupy more space, and the cost would be much higher. Whole-house air purifiers, such as those installed within HVAC systems, are very good at bringing in clean air. However, many pollutants do not come from within these systems and cannot solve the abovementioned issues. The pollution can come from people, windows, chemicals used in the room, or others. A novel smart moving local purifier is a solution to resolve the previously discussed limitations.

Air purifiers containing high-efficiency particulate absorbing (HEPA) air filters and carbon filters are good at removing pollutants, but their ability to remove viruses from the air is very minimal. Due to this limitation of being inefficient with viruses, it takes many passes to remove large numbers of viruses from the air. The alternative is to use Ultraviolet C (UVC) lamps that can remove almost all viruses, including COVID-19, from the air, increasing people's safety in that area. There are three forms of Ultraviolet (UV) light: UVA (315–400 nm), UVB (280–315 nm), and UVC light (200–280 nm).[11] UVC is the shortest wavelength of the three forms of UV, and it is a more harmful type of UV radiation. UVA and UVB come from the sun but have limited germ-killing ability. UVC can kill bacteria and viruses without harming humans with low direct contact with people. Hospitals use UVC lights to disinfect their rooms.

Humid air rises, so it gets replaced by less humid air. Humidity takes a while to travel from one side of the room to another. Usually, the area around a humidifier is very humid compared to the rest of the room. Due to the many benefits of optimal humid air, humidifiers need to be moved around a large space to get more evenly distributed humidity. Alternatively, many small humidifiers are required to humidify a large room more uniformly.

Each component, the air purifier, humidifier, and UVC lamp, is essential to people's benefit and safety, but they may not be as efficient on their own. Most air purifiers and humidifiers need to move around for maximum efficiency. This is especially true for huge rooms. A device that moves would increase effectiveness and uniform distribution.

When a person living alone enters a medical emergency, they can make efforts to call 911 or their family or friends using a land phone or a cell phone. However, when people fall and become severely injured or unconscious, making a phone call becomes difficult. Also, when there are window break-ins or deafening noises like gunfire, the person attempts to hide and may not have a phone device to make an emergency call.

Various devices with special functions are needed in different rooms to solve multiple issues. This project attempts to solve a novel smart artificial intelligence (AI) based moving air purifier, sanitizer, and humidifier/ dehumidifier with the emergency alert system.

Methods

Robot Optimal Design for maximum performance:

This project aimed to develop a robot that not only cleans, purifies, and humidifies the air but also detects visual and audio anomalies. For this to happen, it needs a subsystem for each task and a navigation stack to control the movement. The functional block diagram of various modules, components, and devices (Figure 1) illustrates a data processing and AI environmental anomaly detection configured to improve air quality and provide emergency alerts. To get started with multiple design ideas, Computer-Aided Design (CAD) software was used to design the robot to create a blueprint for visualization and placement of the required electronics.

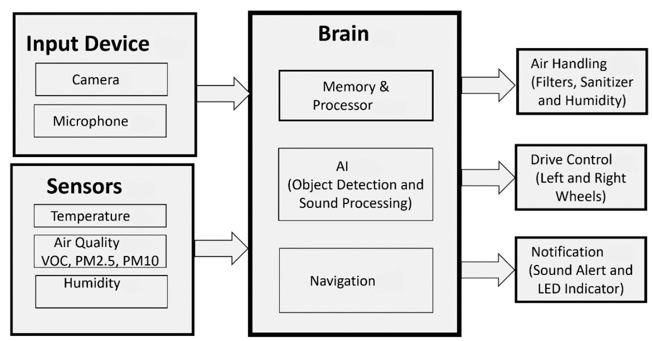

Figure 1: Functional block diagram of various subsystems.

Robot Modeling using Computer-Aided Design:

There are many possible designs for a robot. Since the most significant aspect of the robot is the air purification system, it was designed first, and then all the other systems were designed around it. Two significant fan designs include a blower fan that draws air from the front and blows it to the top and a radiator fan that pulls air from the front and blows it to the top. HEPA filters are used since it is the industry standard for air filtering. A UVC lamp is included in the design to deactivate viruses and kill bacteria. Various design ideas were thought through, and finally, the two main air chamber designs were narrowed down. Design 1 pulls air through a cylindrical filter and blows it to the top (Figure 2), while Design 2 uses a blower fan to pull air from the front of a rectangular filter and blow air to the top (Figure 3). The two designs were

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analyzed further to pick the best design. The approach to using Computational Fluid Dynamics (CFD) analysis as the next step from CAD design was followed to select the model with the highest efficiency.

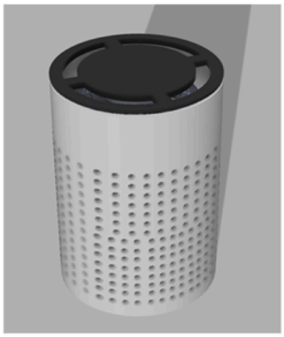

Figure 2: Design 1.

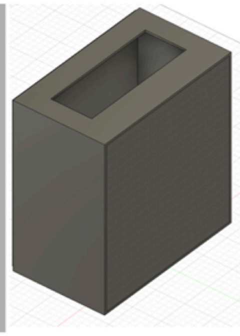

Figure 3: Design 2.

Optimal Design through Computational Fluid Dynamics:

Computational Fluid Dynamics (CFD) is mathematically modeling a physical phenomenon involving fluid flow and solving it numerically using computational prowess. The Navier-Stokes (N-S) equations are specified as the mathematical model of the physical case. A CFD software analysis examines fluid flow in accordance with its physical properties, such as velocity, pressure, temperature, density, and viscosity. The main structure of thermo-fluids examination is directed by governing equations based on the conservation law of fluid's physical properties. These principles state that mass, momentum, and energy are stable constants within a closed system. Everything must be conserved. Model establishment followed the basic four procedural steps:

Step 1: Specify the problem parameters, including boundary and initial conditions.

Step 2: Build the CFD model.

Step 3: Calculate a solution.

Step 4: Examine the results.

CFD analysis was conducted on these two designs to check peak velocity. Both designs were set up using the respective CAD models. Design 1 had a higher peak velocity (Figure 4) at around 2200 cm/sec than Design 2's 1800 cm/sec (Figure 5). As a result of the higher airflow, Design 1 was selected for the robot (Figure 6).

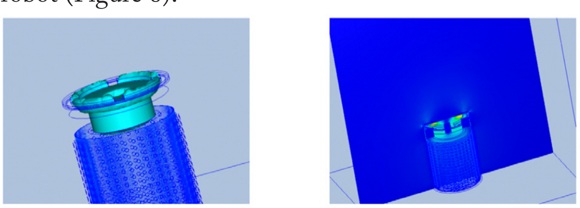

Figure 4: Design 1. CFD analysis with cylindrical HEPA air filter.

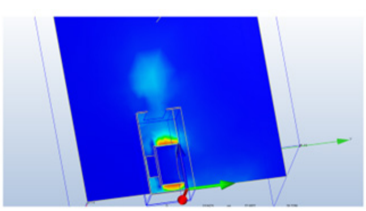

Figure 5: Design 2 CFD analysis with rectangular HEPA air filter.

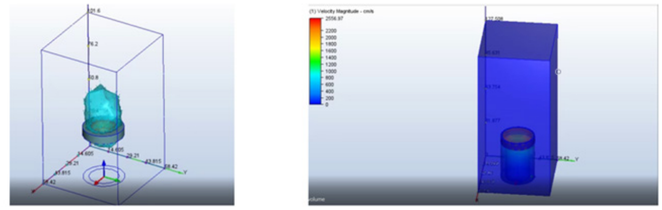

Figure 6: Final design analysis.

Final CAD design:

After choosing the first design, the CAD model was further expanded to include all aspects of a finished robot (Figure 7). The UVC chamber rests on top of the fan, and the humidification system is on top. Originally an ultrasonic humidifier was used, but it was changed to a vaporization humidifier by using a cloth wick that soaks up water, evaporating as the purified air blows through the sponge. The dehumidifier can optionally be placed on top instead of the humidifier if humidity is higher than normal. The Light Detection and Ranging (LiDAR) is located at the top. The Intel tracking camera for Visual Simultaneous Localization and Mapping (vSLAM) is placed at the front, along with the Intel depth camera used for AI object detection. The rest of the electronics are placed on the bottom.

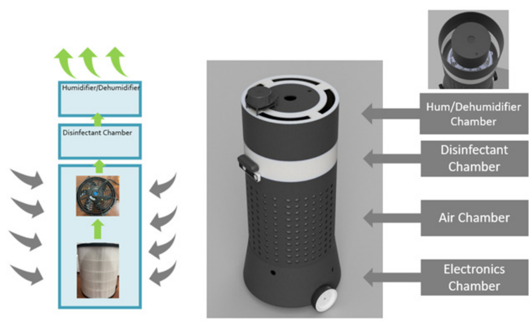

Figure 7: Robot design and render.

Physical Prototype Development:

The robot consists of hardware and software portions. The hardware consists of the physical structure that operates on two wheels, processors, sensors, batteries, etc. The software includes the Robot Operating System (ROS) with a set of libraries that performs various functions.

Hardware:

Once the detailed CAD design was completed, the robot was 3D printed using Poly Lactic Acid (PLA) filament and assembled. The electronics were attached and wired up. The various stages of the prototype process are shown (Figure 8).

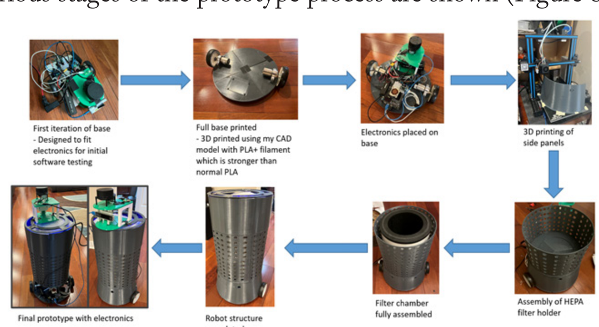

Figure 8: Robot prototyping stage.

The brain and sensors are all part of electronics and sit inside the electronics chamber. The electronics are all mounted on the base and bottom of the air handling system. The brain contains memory and a processor which receives data from the sensor system, camera, and microphone to perform multiple operations, including AI to process the data for navigation of the smart robot. The block diagram shows these components (Figure 9).

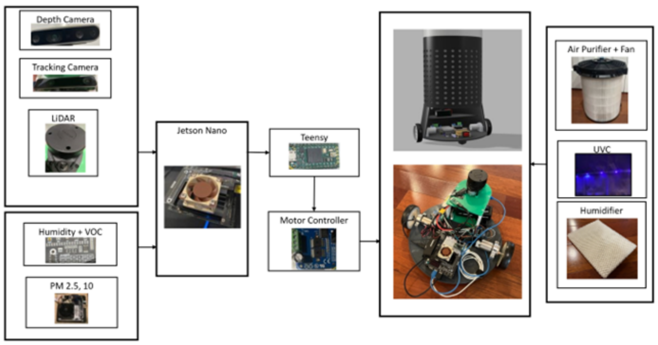

Figure 9: Diagram of electronic components.

The drive controller mounted on the base receives instruction from the navigation module of the brain. In turn, the drive controller provides instructions for the speed and direction change for the left and right motors. The two wheels mounted on either side of the base move with power and control from two individual motors. The two motors independently drive their wheels. Two metal ball bearings are mounted at the two ends to keep the robot stable.

A sensor system has multiple sensors mounted inside the electronics chamber to obtain real-time air quality data and other surrounding metrics.

As part of air quality, volatile organic compound (VOC) sensors are used to measure a wide range of VOC intended for indoor air quality monitoring of the environment. The sensor can measure total VOC concentration within 20 to 1000 parts per billion (ppb) with about 2% to 5% error. It can detect alcohols like benzene, toluene, and formaldehyde. It also detects aldehydes, ketones, organic acids, amines, organic chloramines, and aliphatic and aromatic hydrocarbons.

The particulate matter sensors PM2.5 and PM10 are used to detect smoke particles from 0.10μm to 1.0μm diameter, dust particles from 0.50 μm to 3.0μm diameter, and pollen particles with sizes from 5.0μm to 11μm in diameter. The particulate matter per 100ml air is categorized into 0.3um, 0.5um, 1.0um, 2.5um, 5.0um, and 10um size bins. The PM sensors are mounted on the base.

The humidity sensor is used to measure humidity levels between 10 and 90% with a 2% error. The temperature sensor is used to measure reading between -40˚F and 150˚F with ±0.5˚F accuracy. This sensor is mounted alongside the humidity sensor. A microphone is used to capture audio in the environment. The frequency response range is from 15Hz to 20kHz. This microphone can capture the glass-shattering waves, which are roughly 556 hertz. A camera is mounted on one side of the air handling system.

Lithium Polymer (LiPo) batteries power all electronics on board. A power supply and adapter are used to charge the LiPo batteries when the robot is turned off and docked to the regular wall power supply. The fans, humidity module, brain, and drive controller are all powered by LiPo batteries. The VOC sensor, the PM2.5, and PM10 sensors, the humidity sensor, and the temperature sensor are powered by the brain and in operable communication with the brain. The two input devices for audio and video: the microphone and the camera, are powered by the brain and in operable communication with the brain. The drive controllers power the motors, which rotate the wheels for the smart robot to traverse the floor. The sound and LED indicators are powered by the brain and are connected to the side of the air purification system.

Software:

The multiple aspects of the robot were connected by using Robot Operating System (ROS). Each sensor has its own ROS topic to publish its data, to which the main program then subscribes to (Figure 10) as per the pub-sub model of ROS. The robot has an environment module that contains temperature, humidity, and VOC values. The PM2.5 and ten sensors also publish their values onto their respective ROS topics. The AI algorithms send their data through their own ROS topics as well. The LiDAR and tracking camera are used to map and navigate the data generated. The navigation uses the navigation stack, takes a 2D nav goal as input, and outputs a cmd_vel that gets sent to the Teensy, a small microcontroller that drives the motors and the robot. The data from the air quality and humidity sensors also control the fan speed through the Teensy based on the set thresholds. There are motor controllers that take in the battery power and the data from the Teensy, which power the motors of the wheels and fan.

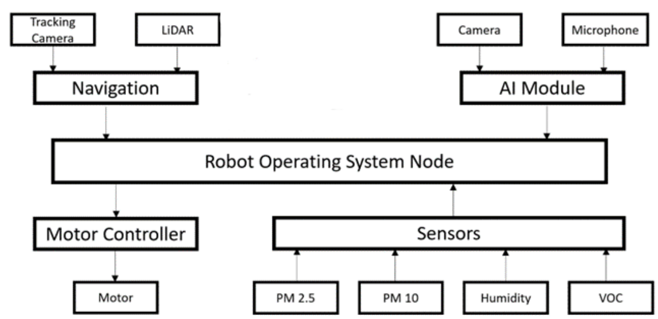

Figure 10: ROS communication diagram.

The navigation module uses air quality data from sensors, humidity data, and an AI object detection algorithm for people recognition with inputs through the camera, as shown in the flow chart (Figure 11). It also uses the stored map for its path planning algorithm (Figure 12).

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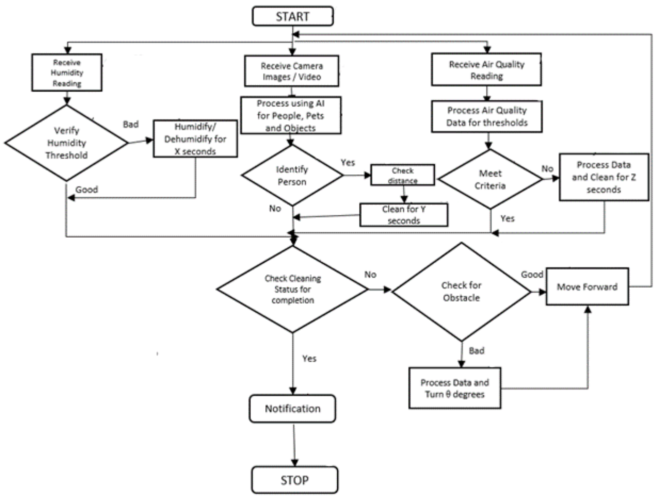

Figure 11: Navigation of the robot.

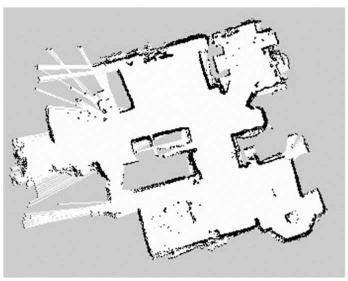

Figure 12: Robot-generated map.

The humidity sensor provides the humidity reading. This data is checked to see if they are within the humidity threshold. An ideal humidity range between 40% and 60% is used as a default. When the humidity level is either low or high, then the humidifier or dehumidifier runs for a certain amount of additional seconds at this location based on the logic programmed inside the navigation module. After this, or when the humidity threshold is good, then the navigation system flags internally that this area is at a satisfying level and would continue into the next step, waiting for the cleaning status of air quality.

Inside the navigation module, the camera feed is received images and videos as a parallel process. The data is processed using AI for people, pets, and objects. The program calculates the additional cleaning time at this location based on the data. After this, when no person is identified, then the navigation system flags internally that this area is clean and would continue into the next step, waiting for the cleaning status on the humidity and air quality.

The air quality reading is received from air quality sensors. This data is processed to see if they meet various air quality metrics criteria thresholds. One criterion for the particle sizes per volume is below 15.0 µg/m^3 or 12.0 µg/m^3 for smoke particles, dust particles, pollen particles, etc. The maximum allowable air concentration of total VOC is below 0.50mg/m^3. When the air quality threshold is not met, based on the air quality data, the navigation module determines the need to run the smart robot at this location for more time after this or when no person is identified, then the navigation system flags internally that this area's level is satisfied and continues into the next step, waiting for cleaning status on the humidity and person detection.

The navigation module calculates and uses the maximum of X, Y, or Z seconds to stay in one location. This cleaning time calculation can be overwritten with a fixed value by the user setting. This maximum time for one location is limited to about 30 seconds, after which the smart robot operates in default autonomous mode.

AI components: Audio & Video:

The environmental anomaly detection is powered by a sound classification system and an image classification system. The flow chart shows the logic used (Figure 13).

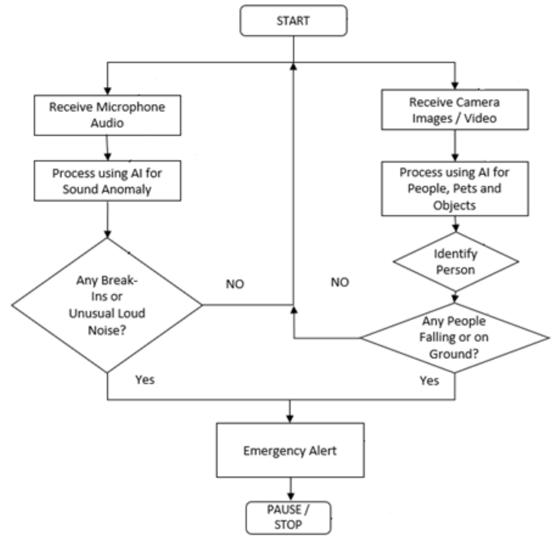

Figure 13: AI system flow diagram.

The camera provides a video feed to the AI-based object detection module of the brain. This model is a TensorFlow object detection algorithm trained on the COCO dataset and based on the YOLO (You Only Look Once) framework. Transfer learning was then used to make the model more lightweight to work on lower-powered devices. As in Figure 16, the data is received, and the AI module is processed to detect people, pets, and objects. When a person is detected with data from the camera and by the AI module, it then checks the person's orientation to determine if the person has fallen. If so, the smart robot sends the medical emergency alert to a smart device notification.

The detection of sound was done using a PyTorch model. A custom dataset was created to include samples from baby crying, glass breaking, gunshots, smoke alarms, someone falling, and background sounds (for control). This new dataset was used to train a Support Vector Machine (SVM), Random Forest, and K-Nearest Neighbors (KNN) using the framework to find the best-performing one.[12] Ultimately, the Random Forest model was selected for its second-fastest response time and highest accuracy.

Results and Discussion

Initial Experiment Research:

Preliminary experiments were conducted to validate the issue of air quality and humidity distribution. Since a standalone device is usually placed in one corner of a room, it may not be able to have an equal overage of said room. A typical single-bedroom home (Figure 14) with an office room could be a two-bedroom home. The initial experiment was conducted with a humidifier in one corner of the 15' x 18' room. Five trials were conducted with two sensors that logged the humidity, PM2.5, PM10, and VOC values. For the trial, one group of sensors was placed near the device, and the other group of sensors was placed farther away on the other side of the room.

Figure 14: The layout of the rooms was tested.

The graph (Figure 15) shows the change in humidity over time for both sensors. The sensor close to the humidifier rose steadily over time and reached the safe 40% threshold, but the device further away did not rise as much and did not reach the 40% threshold. The humidifiers used for this test were ultrasonic humidifiers. As the test was conducted, the observations were that the overall air quality dropped. We noted this as the water is not pure since there are minerals in the water and possibly mold. As a result, we decided that the robot should use vaporization-based humidifiers since those humidifiers do not release any pollutants.

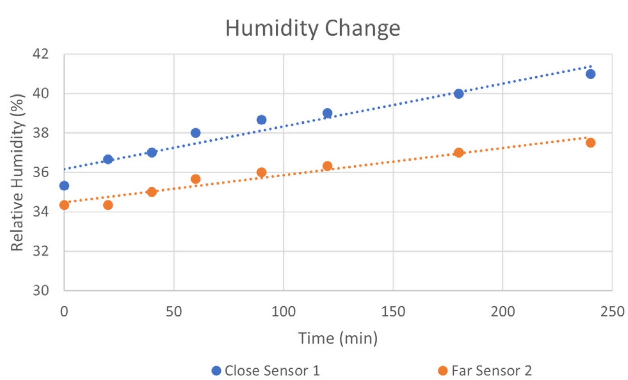

Figure 15: Humidity measurement with one humidifier at a fixed location.

Air quality was retested next with an ultrasonic humidifier providing the pollutants for the air. The change in air quality for the two locations with a standalone air purifier was uneven (Figure 16). Similar to humidity, the air quality improvement rate is based on the closeness to air purifiers, with only the close sensor reaching a safe level of particulates.

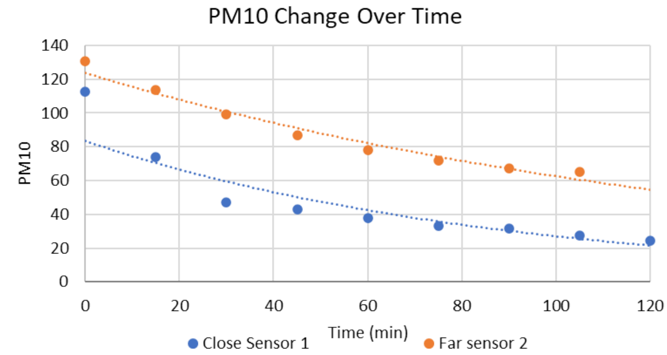

Figure 16: PM10 changes over time with one air purifier.

Further experimental trials were conducted to see the impact of two humidifiers and two air purifiers distributed in the same size, 15' x 18'. Similarly, the air purifier was placed further apart in an attempt for distribution. The trial and data, as in the above experiment, were conducted. The result was much more encouraging, as the humidity and air quality are much more uniform.

Robot Evaluation and Data Analysis:

The evaluation experiments were repeated, except the robot was used instead of the standalone devices. When humidity was tested, both the near and far sensors noticed similar increases in humidity over time, reaching the 40% threshold of safe humidity (Figure 17). On the other hand, air quality still performed, with both sensors displaying similarly decreasing values (Figure 18). They both approached the safe level of 30-40ppm. This shows that the robot is effective at distributing clean air evenly. On top of this, the AI modules were evaluated with good results. The robot effectively performed the even distribution throughout the room for both air quality and humidity. This would be an excellent device to use, especially in this pandemic, as many people are staying indoors, and the removal of COVID-19 with this robot using the UVC LEDs. This product can benefit those who need it even during normal times.

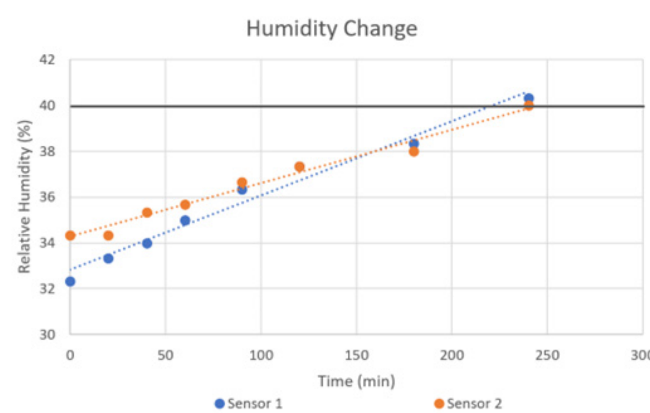

Figure 17: Humidity change over time with robot for close and far sensors, respectively.

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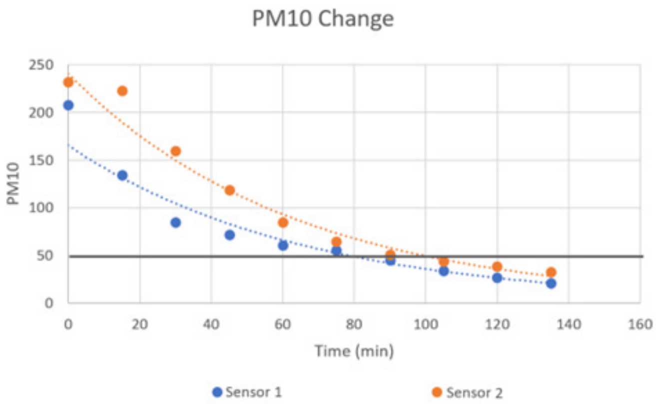

Figure 18: PM10 changes over time with the robot.

Conclusion

This project constructed a smart robot to purify, humidify, dehumidify, and disinfect the air evenly. The mobile robot automatically removes dust and pathogens and maintains stable humidity evenly across the chosen space. Additionally, the robot detects environmental anomalies, keeping people safe in its operating space.

The ability of the robot to travel between rooms reduces the time needed to move multiple devices manually and eliminates the need for these devices. The environmental anomaly detection, comprised of video fall detection and audio anomaly detection, was able to detect falls and anomalies in the real world during testing.

The robot was able to improve on the existing standalone devices. People will not have to get multiple devices to perform various functions as outlined at the beginning. The robot should be commercialized in schools, homes, hospitals, offices, and nursing homes to provide cleaner air and a safer environment.

Acknowledgments

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