Robotic Cleaning and Air Sealing of Attics

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***Abstract*— Buildings contribute to about one third of carbon emission in the U.S. EPA estimates that homeowners can save an average of 15% on heating and cooling costs by air sealing their homes and adding insulation in attics and floors over crawl spaces. Yet, today many U.S. attics are not being air sealed due to inaccessibility. There are three parts to attic retrofit: cleaning, air sealing, and blowing in new insulation. In this paper, we describe two robotic systems for cleaning and air sealing single family residential homes. We use off the shelf base robots with custom designed payload for each task. We have tested the vacuum cleaning robot in an actual home in Sonoma, CA.**

***Keywords*— Robots, air sealing, attic, vacuum cleaning, payload, energy savings;**

I. Introduction

EPA estimates that homeowners can save an average of 15% on heating and cooling costs by air sealing their homes and adding insulation in attics and floors over crawl spaces. Yet, today many U.S. attics are not being air-sealed due to inaccessibility, and unwillingness of workers to crawl in the tight, unhealthy, hazardous spaces. We have developed a robotic attic vacuum cleaning and air sealing systems for inaccessible attics and confined spaces. Our suite of products consists of two layers of Thermadrone software systems sandwiching Robo-Attic hardware retrofit robots. First, Thermadrone software uses thermal drone camera images captured with commercially available drones to diagnose and identify attic retrofit opportunities. As such, it serves as a market and pipeline development and customer acquisition tool. Second, RoboAttic robots enable contractors to both vacuum clean and air seal attics faster, cheaper, and safer, in addition to allowing them to retrofit attics that are inaccessible by humans and would not have been air sealed otherwise. Third, Thermadrone software allows for measurement and verification (M&V) after completing the retrofit job, thereby de-risking projects by proving out quality assurance. In tandem, these will unlock revenue for contractors and lower the price for and provide energy savings to homeowners.

The block diagram of our diagnostic/retrofit/M&V system is shown in Figure 1. The two blue boxes represent the diagnostic part of our system consisting of (1) drone RGB and thermal image capture which is fed into (2) our interactive visualization software tool to identify homes in need of attic retrofit. The two orange boxes correspond to our robotic solutions for (1) cleaning and (2) air sealing; The two yellow boxes correspond to M&V process, with the first box representing post retrofit drone image capture, and the second box our M&V software tool. A side benefit of our system in Figure 1 is a stud location method represented by two salmon color boxes. It uses drone captured thermal imagery to detect studs from the exterior, and can be used in other envelope retrofit projects such as recladding exterior of buildings with insulation panels. This is an important application, even though it is entirely unrelated to attic retrofit. In what follows, we will describe each of the above subsystems in more detail.

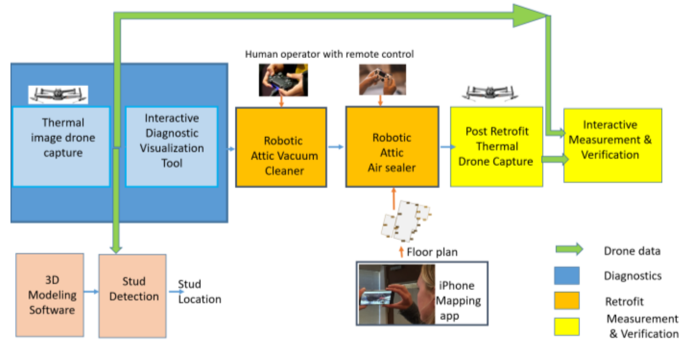


Figure 1: Overall block diagram of our system.

II. Motivation and Design Choices

Our robotic prototypes address the problem of cleaning and air sealing attics and confined spaces. These cannot be easily air sealed or insulated with current technology without major disruptions to building occupants. As a result, many of these spaces are left uninsulated and un-air sealed. Attic spacing in flat/low slope roofs typically ranges from 20” at the height of the attic to 10” or less at the bottom of the roof slope. Very few air sealing technicians are willing to climb into this extremely tight space. Those who do access these spaces find that almost half the attic is inaccessible. The unwillingness of most air sealers to undertake this type of extremely frustrating and dangerous work is entirely understandable. While inaccessible attics are left completely uninsulated, confined attic spaces are often poorly insulated. In ranch style homes and other residential building types with shallow roof pitches, workers simply cannot reach into the critically important wall/roof transition between the rafters and top plates.

To address these problems, we have developed robotic attic vacuum cleaning and air sealing systems for inaccessible attics and confined spaces. The cleaning system crawls through attic spaces and vacuums loose insulation and other debris on the attic floor. Once the attic has been cleaned, the air sealing robot dispenses spray foam material into gaps in the floor surface of the attic. The ultimate goal is to create an unconditioned air sealed attic with little or no air leaking from the main structure to the attic.

Design Choices: In designing our RoboAttic system, we interviewed a large number of stakeholders including attic contractors, foam manufacturers such as ICP, DAP and

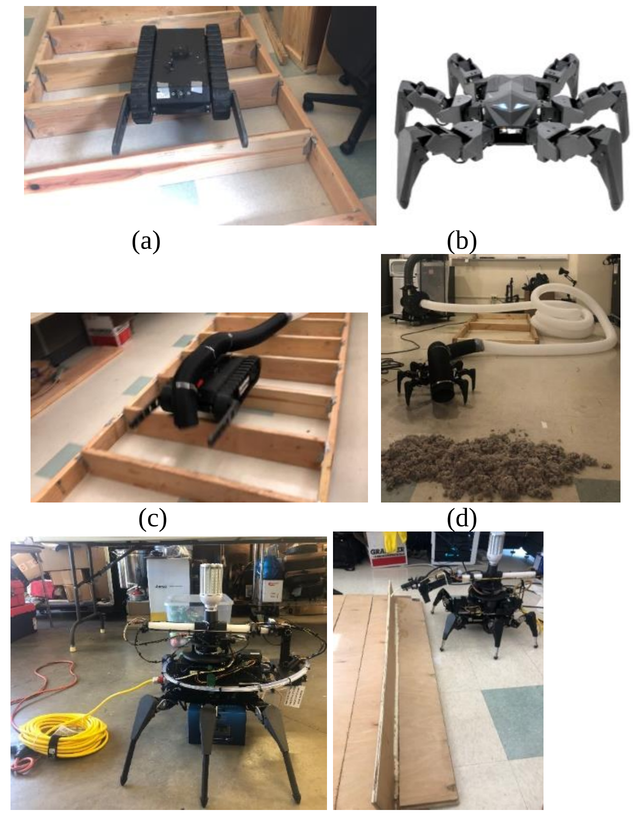
DuPont, as well as dispensing system designers such as Graco. In doing so we discovered the following facts which shaped our design choices: (a) Typically cleaning the attic is a more time consuming task than air sealing it by a factor of 2 or 3. In addition, cleaning is considered to be more undesirable by workers, as they have to deal with not only old insulation, but also other debris such as animal feces. (b) Completely eliminating human from the air sealing process is difficult if not impossible. To begin with, for large gaps such as plumbing or electrical chases, there is a need for a human to cut a rigid board matching the size of the gap, which is then spray foamed. Similarly, if vent baffles are not already installed in the attic, then a human would have to do that installation, followed by spray foaming. Ditto with canned lights. As such, the best one can achieve with a robotic system is to help the human operator to get the job faster, better, safer and cheaper, but they cannot be completely eliminated; (c) The choice between one and two component foam is an important one, and has implications on our air sealing payload and its associated dispensing systems. While the two component foam can fill out larger gaps than one component foam (OCF), its nozzle would have to be replaced after 30 seconds of non-use, making it impractical in a robotic system. As such, we have opted to use OCF for our robotic air sealing payload. (d) When insulating an attic, one can create either a conditioned attic or unconditioned attic. Our goal in this project is to create the latter by air sealing the attic floor.

III. Base robots and payloads

We have developed two distinct base robots, namely hexapod and tracked, in combination with two distinct payloads, one for cleaning and one for air sealing. We can mix and match these with each other resulting in four configurations. The choice of base and payload depends on many factors including the size of the attic, the weight its sheetrock can tolerate, level of clutter in the attic, the distance between joists i.e. 16" or 24" on center, and the task at hand i.e. cleaning vs air sealing. Broadly speaking the tracked robot is faster but heavier, and less maneuverable than the hexapod robot. For a thorough analysis of pros and cons of the two base robot, see the Design Specification document. Figure 2(a) shows a tracked robot with arms, capable of traversing on top of a row of joists 16" apart. Figure 2(b) shows the hexapod capable of climbing over the joist structures in attics by lifting its legs in groups or one leg at a time. Figures 2(c) and 2(d) show the vacuum payload on top of tracked and hexapod robots respectively. Figures 2(e) and 2(f) show the air sealing payload on top of the hexapod base.

IV. Locomotion and navigation

As for the locomotion of the base robots, both controllers allow for moving forward/backward and right/left. The operator navigates around large objects which the robot cannot climb over. S/he uses the joystick to climb over joists by invoking pre-programmed sequence of leg movements for the hexapod; for the tracked robot the operator uses the arms to climb over and traverse over joists as seen in Figure 2(a). For both base robots, there is a remote monitor which shows the live video feed from the camera on the robot. This allows the user to operate the robot without line of sight. An example of this is shown in Figure 3(a). For base robot locomotion, we use PS4 controller shown in Figure 3(a) for the hexapod, and Flasky controller shown in Figure 3(b) for the tracked robot. Both remote controllers have two joysticks and extra knobs that allow for the needed movements of the payloads.

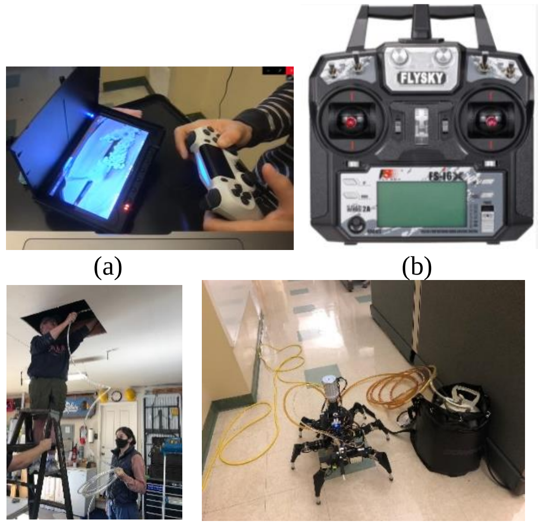


(a) (b) (c) (d) (e) (f)

Figure 2: (a) Tracked Robot with no payload; (b) Hexapod robot with no payload; (c) Tracked robot with vacuum payload; (d) Hexapod robot with vacuum payload; (e) Hexapod robot with air sealing payload; (f) hexapod root air sealing a gap .

V. Concept of operation of the cleaning system

As stated earlier, before an attic can be air sealed, it needs to be cleaned. The cleaning process involves removing the old loose insulation, and other undesirable debris in the attic such as animal feces. Today, cleaning is accomplished with a large 4" or 6" diameter vacuum hose, of length 50' to 100' attached to an insulation removal vacuum machine ranging anywhere from 10 to 20 Horse Power (HP). The concept of operation for our vacuum cleaning robot is as follows: the operator connects the back end of the vacuum hose on the robot, which is black in Figures 2(c) and 2(d) to the 50' vacuum hose, shown in white. The other end of the white hose is connected to the insulation removal vacuum machine. S/he then places the robot at the entrance to the attic by removing the attic hatch as seen in Figure 3(c). The dimensions of both base robots, tracked and hexapod, are small enough to fit most existing attics in single family residential homes in the U.S. Once the robot is in the attic, the operator controls the movement of the base robot, be it hexapod or tracked, and the orientation of the hose using the remote control systems. In the case of the vacuum payload, this would be one degree of freedom allowing the vacuum hose tip to move right/left.



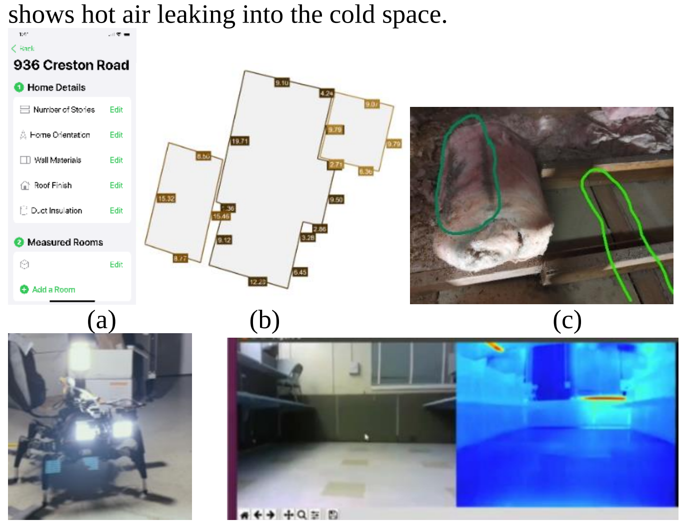
(a) (b) (c) (d)

Figure 3: (a) Remote operator with a video monitor and PS4 controller for the hexapod; (b) Remote control Flask system to be used in conjunction with a display monitor to control the tracked robot. (c) Robot with air sealing payload being placed through the attic hatch. (d) Hexapod robot with air sealing payload connected to a 25' hose and a tank with heating blanket.

VI. Concept of Operation of Air Sealing Payload

The air sealing system operates after the attic has been cleaned. The air sealing payload is connected to a 3/8" diameter 25' hose, which at the other end is connected to an OCF pressurized tank as seen in Figure 3(d). The concept of operation for the air sealing system is as follows: The operator places the robot, the 25' hose, and the tank at the entrance to the attic as shown in Figure 3(c). S/he then leaves the attic, to remotely control the robot and the air sealing payload. There is a 2500 lumen LED corn bulb, as well as two LED panel lights on the air sealing payload that can brighten up an attic as seen in Figure 4(d). The remote control for both base robots have joysticks and degrees of freedom to control the turret in the air sealing payload shown in Figure 2(e). The operator begins by using the remote control to move the turret and hence the LED lights to the right / left, up/down in order to get an idea of the lay of the land in the attic. Next the operator navigates the robot to the locations in need of air sealing using the joystick and remote video monitor. Once the robot is situated near a gap, the operator spray foams it by controlling the tip of the end effector on the turret using intuitive user interface on the joystick. Specifically, one joystick controls the height of the tip i.e. z axis, and the other creates arbitrary motion in the horizontal x-y plane. An example of spray foaming is shown in Figure 2(f).

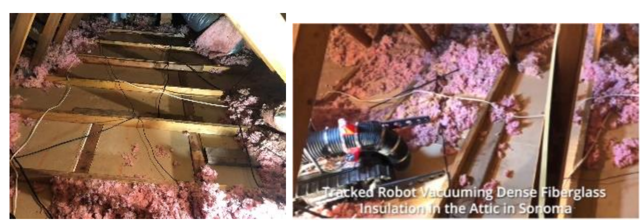
Even though our system is remotely controlled by a user through a live video feed, we aid the operator to locate the most prominent gaps, i.e. at the top of wall plates. Existing methods used by attic contractors consist of door blower test, or pressurization test with a smoke / incense stick. To minimize disturbance to the occupants, we have opted for a different approach. We leverage mobile app, "Remotely" which can be used by the operator or homeowner to rapidly create floor plan of the house ahead of time by simply walking around a house with an iPhone and following a simple set of instructions on the screen. The screenshot of the Remotely app is shown in Figure 4(a), and an example of the resulting floor plan for a 1000 square foot house is shown in Figure 4(b). For a 2000 square feet house, this process takes less than 20 minutes. The resulting floor plan is then loaded onto the robot to help the operator navigate to the gaps at the junction between top plates of walls and attic floor. An example of such a gap is shown in Figure 4(c) where the green lime area shows the top plate in an attic with the flat 2 x 4 connecting to sheetrock. Looking at the fiberglass to the left, the black streaks, circled in dark green show all the dirty air leaking out of the house into the attic. We also detect gaps with the thermal camera on the robot as shown in Figure 4(e) where the right bright line in the thermal picture shows hot air leaking into the cold space.



(a) (b) (c) (d) (e)

Figure 4: (a) Screenshot of Remotely app available on i-Phone; (b) Example floor plan of the main structure of a house created by Remotely; (c) The green lime area shows the top plate in an attic with the flat 2 x 4 connecting to sheetrock; the thin black line is the gap. (d)Robot with all the lights turned on to illuminate a dark attic; (e) Example of using thermal camera on the robot to detect air leaks.

Figure 5 shows the vacuum payload on top of the tracked robot cleaning the attic of a single family residential home in Sonoma CA.



(a) (b)

Figure 5: (a) Cleaned attic; (c) robot vacuuming.

VII. Energy Efficiency

EPA estimates that homeowners can save an average of 15% on heating and cooling costs or an average of 11% of total energy costs by air sealing their homes and adding insulation in attics, floors over crawl spaces, and accessible basement rim joists. This estimate is based on energy modeling of costeffective improvements made to 'typical' existing U.S. homes with a weighted composite of characteristics using Beacon Residential. For the purpose of estimating energy savings, EPA assumed that a knowledgeable homeowner or contractor could cost-effectively seal air leaks throughout the house, focusing on leaks to the attic space, through the foundation, and around windows and doors to achieve a 25% reduction in total air infiltration[1]. Assuming that one half of the reduction in air infiltration is at the attic, our RoboAttic solution results in 8% reduction in total air infiltration, and 7.5% annual reduction in average heating and cooling cost per home. Average US household uses about 77 million British thermal units (Btu) in 2015 and of the energy used in US homes in 2015, 55% was used for heating and cooling. Therefore, 7.5% reduction in heating and cooling results in 7.5% x 77M x 55% = 3M Btu saved per home. Assuming 82 million single family residential homes in the U.S., this results in 0.25 quads per year of energy saved by air sealing attics. Furthermore, according to the US Energy Information Administration, the average cost of energy in US households is about $115.49 a month in 2019—with nearly half of that money, i.e. $58 a month going to heating and cooling[2]. Assuming 82.1 million US homes, the 7.5% reduction in heating and cooling results in 4.3 billion dollars per year of saving.

VIII. Worker Benefits

Environmental health and safety issues present formidable challenges in virtually all attics. Many workers, have been seriously injured falling through ceilings after slipping off joists. In the middle of summer, these spaces are uncomfortable and dangerous, often reaching temperatures of 120 – 140F. Fiberglass dust, rodent droppings and other hazardous materials are almost always present. Applying spray foam in these environments is especially hazardous due to the requirement for full face respirators, hot Tyvek suits and the possibility of spontaneous combustion of spray foam chemicals; one spray foam worker was killed after becoming trapped in a knee wall. All of these factors combine to make it exceedingly difficult to retain skilled insulation workers for work in confined spaces. Lack of workers, in turn, greatly reduces the ability of contractors to expand to meet the needs of various weatherization programs. With our proposed robotic solution, the remote operator can safely stay outside the attic, while remotely controlling the robot to vacuum, inspect, air-seal, and insulate it. The vacuum payload also speeds up the cleaning process by 2X to 3X. To summarize, our proposed solution brings high tech jobs to the industry by allowing the workers to interact with robots via intuitive user interface, improves worker safety in that they do not have to get to inaccessible parts of the attic, enables the workers to be more efficient with their time since they can get the job done faster than by crawling on top of the joists, and increases the number of attics that can be retrofitted, by adding the inaccessible ones to the pool.

IX. Productivity

We start by analyzing the speed of the robotic vacuum cleaning process. The width of each robot is about 20", and the vacuum hose moves from right to left across the 20" width of both robots as they vacuum; for an average attic with 2" of loose insulation, we have shown that at 10 cm/second speed, the robot removes all insulation. This means that for a 1600 square feet square attic of size 40 ' x 40 ', the robot would have to traverse in a lawnmower fashion for about 40'/20" = 24 sweeps to fully vacuum the entire surface area. A sweep is defined as traversing 40' from one end to the other end of the attic. Furthermore, each sweep of 40' length , at 10 cm/second speed, takes about 120 seconds or two minutes. Thus 24 sweeps each taking 2 minutes takes about 48 minutes. This estimate ignores the turning time from the end of one sweep to the next, as well as required arm maneuvering to navigate the joists for the tracked robot, and leg sequence movement for the hexapod. Assuming that these double (triple) the vacuum time for the tracked (hexapod) robot, the total vacuum time is 96 (144) minuets or about 1.5 (2.5) hours. It typically takes 5 hours for two workers to clean up this size attic; thus, we achieve a 2X or 3X speed up depending on whether we use the hexapod or the tracked robot. Even though the tracked robot moves faster and navigates the joists better than the hexapod, and can carry a heavier payload of 20 pounds, it is 3 times heavier than the hexapod, and at 50 pounds, it might not be usable in attics with very thin sheetrock. See the Design document for more details.

We now repeat the above timing analysis for air sealing. Assuming that there are about fifty 1" gaps of length uniformly distributed between ½ meter and 1 meter in a 1600 square foot attic, it would take about 2 hours for either the tracked or hexapod robot to air seal it. This is in par with the speed of a human operator only if the human could reach all tight spots inside an attic.

The tracked (hexapod) robot use Flasky (PS4) remote controller with two joysticks which control the movement of the robot, as well as the movement of the turret for the air sealing and the tip of the vacuum hose for vacuum payload. For the hexapod, climbing over joists is achieved by a push of a button and does not require the operator to do each individual leg movement one by one. We have found that 90% of users can learn the movement of the robots on flat ground in less than 5 minutes, the movement of the vacuum hose in less than five minutes, and the movement of the turret for air sealing in less than 20 minutes. For the tracked robot it takes about 30 minutes for the operator to learn to use the arm to maneuver it around joists.

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1 https://www.energystar.gov/campaign/seal_insulate/methodology#:~:text=Seal%20air%20leaks%20throughout%20the,reduction%20in%20total%20air%20infiltration.

2 US Department of Energy, "Energy Saver." Accessed April 15, 2021