Conceptual Design of a Robotic Building Envelope Assessment System for Energy Efficiency

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Abstract -

Building air leakage and moisture issues can result in significant energy loss, shorten the building envelope life cycle, and require additional maintenance costs. While these issues present risks to a building and its occupants, they could be difficult to detect during building maintenance and early stages of retrofit projects. Currently, mapping air leakage and moisture issues over a building's envelope relies on manual inspections. These methods are intrusive, expensive, and hazardous to inspectors' safety. To address these challenges, we propose a non-invasive and safe conceptual solution, a Robotic Envelope Assessment System for Energy Efficiency (EASEEbot), to locate and document moisture intrusion, thermal bridges, and air leaks. EASEEbot is a high-power wall climbing drone and comes with a multi-function toolbox. It can capture 3D thermal images and auto-generate 3D models using image-based Structure from Motion (SfM) and Visual Simultaneous Localization and Mapping (VSLAM). Our deep learning algorithms will rapidly identify common building envelope defects from multi-modal sensing data. EASEEbot is also designed with a tethered wall-climbing mode and will use long-wave ground penetrating radar (GPR) to detect hidden trapped interstitial moisture and other major envelope defects.

Keywords -

Building Envelope Inspection; Remote Inspection System; Building Moisture; Thermal Leak Detection

1 Introduction

In the United States, buildings account for 28% of total primary energy usage and 40% greenhouse gas (GHG) emissions [1, 2]. To combat climate change, major US cities require energy benchmarking and regular energy audits for large multifamily and commercial buildings [3, 4, 5]. Recently, governments are also offering incentives and programs for low-rise residential building energy audits [6, 7]. Based on previous studies, thermal exchange through the building envelope is one of the primary sources of energy loss. Some studies estimate energy costs could be reduced by up to 20% by sealing the building envelope [8, 9]. Therefore, rapidly detecting and locating areas of significant heat loss and air leakage on the building envelope remains a key challenge for improving the energy efficiency of buildings.

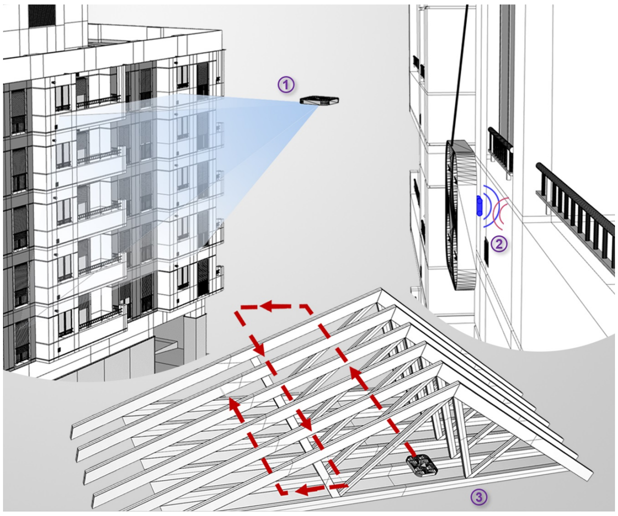

Figure 1. Three main application scenarios. 1. 3D thermal reconstruction of building envelope. 2. Detailed inspection by using GPR sensor and tethered wall-climbing drone. 3. Interior envelope inspection in attic spaces.

Conventional building envelope inspections involve in-person site visits and manual mapping of located issues on paper documents. Depending on the size of the building, inspectors can spend a significant amount of time surveying an entire envelope. Inspectors may also need to access hazardous areas like roofs, elevated exterior wall sections, and attic spaces without structural flooring [10]. Considering their own safety and productivity, inspectors will typically limit the scope of their envelope assessments, only examining a select number of representative areas. With the popularity and improved reliability of drones, recent research has proposed to use drones to assist envelope inspectors in accessing hazardous building areas

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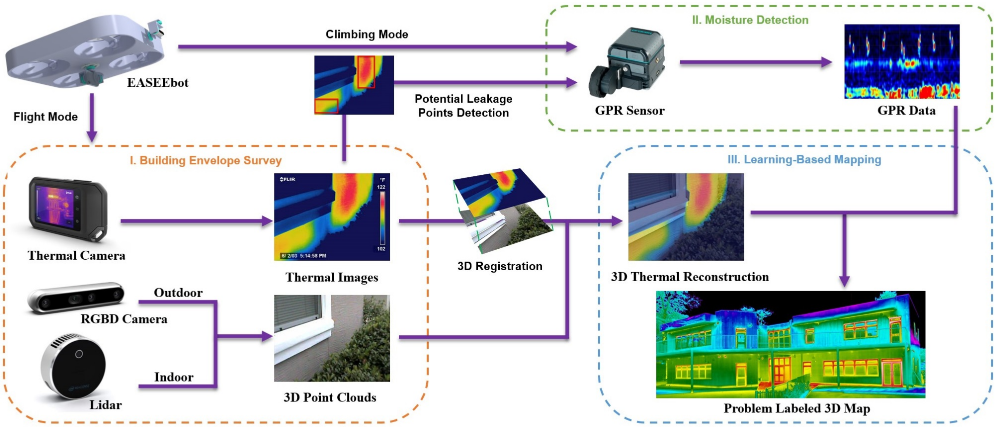

Figure 2. Our conceptual workflow. I. Building envelope data collection and defect detection. II. Detailed detection of wall moisture content by using GPR sensor. III. 3D reconstruction with thermal data and overlay with detected defect locations.

and detecting envelope issues over a larger area with less physical effort and time [11].

Current conventional testing often involves an invasive blower door test [8] which pressurizes the building and forces occupants out. Less invasive infrared thermography (IRT) can find specific air leakage pathways, thermal bridges, and trapped moisture [12, 13]. However, IRT images can be easily distorted by sunlight or reflectance and require a highly trained and specialized thermal imaging experts. IRT images are also not reliable for detecting moisture deep within envelope assemblies. Recently, research has attempted to utilize Ground Penetrating Radar (GPR) to detect hidden envelope moisture by analyzing radar images [14].

In this paper, we propose an automated energy loss detection solution for building envelopes. As shown in Figure 1, various modular sensors can be attached to the drone for scanning the building envelope in different scenarios. In Section 3, we demonstrated our solutions in three different simulation environments. Future work on the proposed prototype will develop a proof of concept for assistance on real-world building retrofit projects. The following are our main contributions in this paper:

- We propose a quadcopter, EASEEbot, equipped with an RGBD camera, thermal sensor, and GPR sensor to automatically survey a building envelope in less time, especially over hazardous and inaccessible areas.
- We design a multi-function robot toolbox to support EASEEbot. It can be used as a storage case during travel or as a power source for EASEEbot in its tethered wall-climbing mode.
- We integrate thermal data with image-based SfM and VSLAM algorithms to generate 3D thermal reconstruction data.
- We present our entire workflow in three simulation scenarios.

2 Related Work

Our robotic system is based on various past research in robot-assisted building inspections and sensing technologies. While past research has attempted to standardize a framework for in person building envelope inspections, our paper is focused on developing specific robot and sensing capabilities for inspectors where they most need assistance [15]. In this section, we will discuss past developments of drones and portable sensors for building inspections.

Inspection Sensors. Most state-of-art inspection methods prefer non-invasive instruments. Compared with invasive inspection, non-invasive devices may involve less setup time and avoid requiring occupants to leave the building. The most significant source of energy loss in building envelope assemblies is heat transfer through direct air leakage pathways, which can be indicated by moisture condensation. Checking envelope airtightness and moisture level of building envelope sections are primary items on inspection checklists.

Cooper et al. [16] developed a low-pressure pulse pressurization technique to avoid large fluid flow and monitor the building envelope in real-time. Recently, Casillas et al. [17] introduced Micro-electromechanical systems (MEMS)-based sensors into building monitoring systems to establish two absolute pressure sensors for determining pressure differences between different locations in buildings.

As an alternative to traditional wall moisture meters and

Figure 3. Simulation in three scenarios: low-rise residential building, commercial high-rise building and roof attic interior.

GPR scanning, detection methods using different material properties have been proposed for the moisture sensors. Healy and his team [18] utilized the change of optical fiber's refractive index in different moisture levels. Mergu et al. [19] accounted for chemical properties to detect moisture levels in the wall section by colorimetrics.

Inspection Robotic Solutions. The current state-of-art solutions for building envelope inspection are mainly focused on portable and automated approaches. Portable refers to the use of smartphone computing power to process and visualize the inspection results by communicating with additional sensors. Wang et al. [20] implemented a deep-learning-based building façade damage detection method and used a smartphone camera for real-time inspection. By using mobile robots or drones as vehicle platforms, researchers could attach various sensors and apply algorithms to detect issues across the entire building envelope automatically. Rakha et al. [21] presented a solution using drones and thermal cameras to survey the building envelope and map the heat loss areas rapidly.

3 System Design

Our system contains a multi-function toolbox and a dual mode quadcopter drone, EASEEbot. In section 4, we present the details of our hardware design. To achieve automation, we integrated a learning-based visual algorithm with drone flight control to automatically combine 3D point clouds with thermal imaging data. All of the software algorithms are introduced in section 5.

System Workflow. As Figure 2 shows, we propose a workflow from building envelope surveys to issue-labeled 3D maps. First, our drone will fly around the building along a user-specified trajectory. During flight, the onboard RGBD and thermal camera will simultaneously record 3D point cloud data and thermal data. This step will locate areas of high heat loss and help the inspector quickly assess the building envelope's overall condition. For each area of high heat loss, GPR can be used to understand the damage level inside of envelope assemblies. Unlike the working principle of other sensors, GPR needs to be in direct contact with the inspection surface. To this end, we need to switch our EASEEBOT to its climbing mode. Throughout the building envelope survey, the inspector's tablet will update, integrate, and visualize the collected data from different sensors onto the building's 3D model.

Workflow Simulation. To better visualize the entire workflow, we use the Microsoft AIRSIM simulator [22] to present our EASEEbot working in different scenarios. Figure 3 shows the three main scenarios in our simulation: low-rise residential building, commercial building, and interior attic. The entire simulation is done through the third-person perspective. There are three additional windows at the bottom showing the images captured by the onboard sensors. The center yellow box displays the RGB camera on the drone. The depth data is displayed in the left green box. The blue box on the right shows the segmentation image, which will help the algorithm detect the potential air leakage areas. The full video can be seen at: `https://youtu.be/Gr07d4nLkpc`.

4 Hardware Design

Our hardware is mainly composed of three parts: the EASEEbot, a robot toolbox, and different types of sensor attachments. The EASEEbot drone can be attached with different types of sensors to scan the building envelope and find the energy leakage. We can put sensors and drones into the toolbox for convenient transportation or storage. The following is our specific design.

Multi-function Toolbox. The size of the toolbox is: 44.88in (L) x 33.07in (W) x 16.54in (H). The toolbox is made of multiple layers with different materials as illustrated in the Figure 5. From outside to inside, the toolbox has rubber bumpers, the polycarbonate (PC) outer shell, carbon fiber strips to enhance the toolbox's durability, and ethylene-vinyl acetate (EVA) foam used as an inner lining to safely house equipment. Since PC material has been widely used in the luggage industry, it has proven to be an ideal sturdy, lightweight and low-cost shell material. In addition, the internal protective material, EVA, not only firmly holds up the internal drone but also protects important equipment and sensors during transportation or

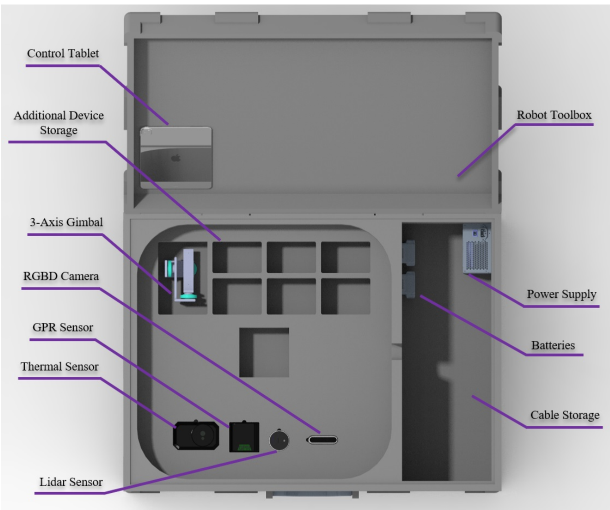

Figure 4. Detailed design of multi-function toolbox

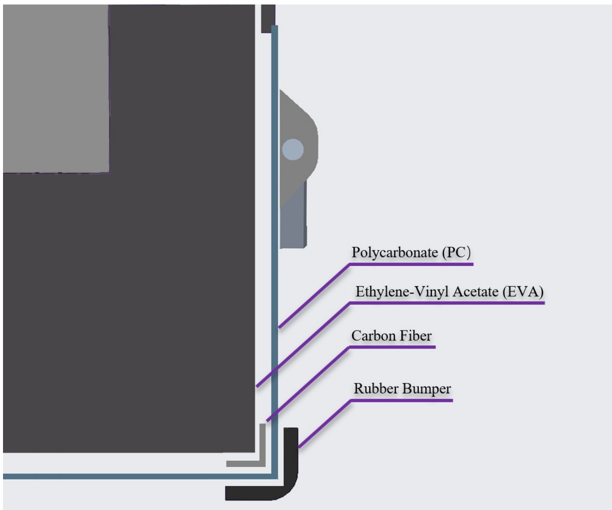

Figure 5. Multiple layers section view of the toolbox

accidents.

As shown in Figure 4, the inside of the toolbox is divided into four zones. We use the lid of the toolbox to place the tablet, user manuals, and work documents. The tablet is used as both a drone controller and real-time data monitor. On the left side of the toolbox is our high-power quadcopter drone, EASEEbot. When the drone is removed from the toolbox, we can place the sensors and other equipment underneath. On the bottom left, there are four main sensors that could be attached to the drone: RGBD camera, LIDAR, Thermal camera, and GPR sensor. Since our drone could directly take off from the toolbox, we designed enough space in the middle of the left side of the toolbox for the gimbal and sensors attached under the drone. The upper left grid is used to place some additional equipment, such as the front gimbal and other sensors that the user may add in the future. The power supply zone is designed on the right side of the toolbox. Space here is used to house power cords, batteries, and external power converters. By setting the battery slot, our toolbox can provide power to the drone when it connects the power cord or charges the drone battery when the toolbox is closed. Many construction workers have cordless tools. In order to save unnecessary costs and more effectively use those batteries, we choose to use cordless tool batteris as our mobile power source. This toolbox also has a built-in 800w DC power supply. When there is a wall plug, we can switch the supply power to an external power supply.

EASEEbot Drone. The size of our drone is 30in (L) x 30in (W) x 5in (H). To ensure flight safety and reduce the technical requirements for the users, we adopted a traditional fully-enclosed quadcopter design. The fully-enclosed design helps prevent a propeller from hitting an obstacle. We use carbon fiber as the main material of the drone's body to provide high structural capacity without increasing its weight. We deployed eight distance sensors around the body to automatically adjust the drone's posture to cross obstacles, such as attic roof trusses. At the bottom of the drone, we set up two Li-Po battery holders and a control board cabin. This drone is designed with two attachment ports. One is in front of the drone, and the other is at the bottom of the drone. Our drone can be installed with two gimbals and inspection sensors through these two ports simultaneously. It can also be attached with one gimbal and use the other port as the external power supply by connecting a power cord.

For the drone to be able to scan the building's facade with its sensors, we designed a four-axes rotation system for each propeller. We installed four motors on rotatable strips. The mini servos are installed and connected to those strips for controlling the rotation angle of the motor. When the drone is under flight mode, we always keep the propellers parallel to the ground. If we switch the drone to the climbing mode, the controller will send commands to the servo motors for rotating an angle and automatically balance the lift force and pressure force through a learning-based control algorithm.

We chose the Nvidia Jetson Nano or Jetson Xavier NX for the the drone's control board. Compared with other control boards, these two Single Board Computers (SBCs) have good computing performance with acceptable power consumption. The main functions of the SBC are to calculate the drone's posture, communicate with the flight controller, collect the sensors' data, and transmit them to the tablet on the ground. The flight controller, which is the driver board for four motors, uses the TXRX interface to communicate with SBC. In our design, we used 4 Turnigy G90 Brushless Outrunner Motors with 15x8 Propellers. Based on the thrust calculator, our drone can provide 12.2kg of thrust, which could let us carry a large

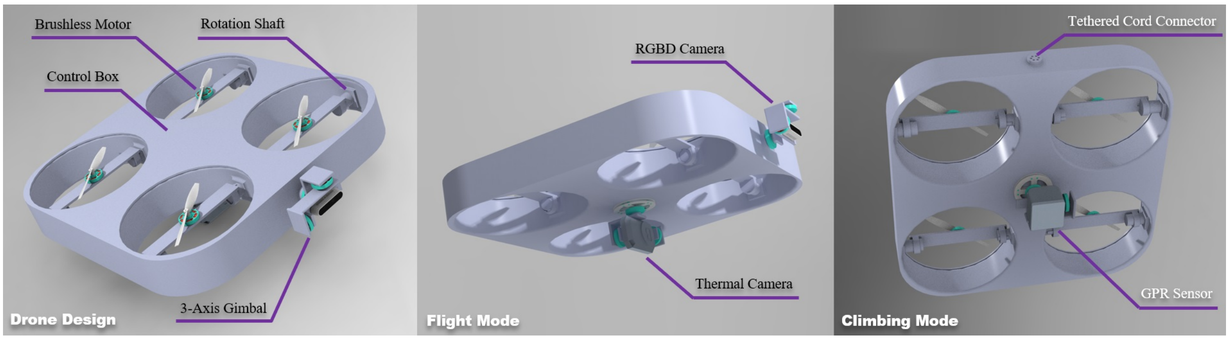

Figure 6. ESAEEbot Design. Left: Drone platform design. Middle: Flight mode sensor setting. Right: Climbing mode sensor and power setting.

capacity battery and sensor equipment.

Operation Modes. Our EASEEbot design has two working modes, fly and climb, to meet the requirements of different sensor attachments. In flight mode, we can quickly survey a building envelope using attached RGB and infrared cameras. The data captured in flight mode can produce an efficient, non-invasive, and preliminary scan of the building envelope's heat loss. Such thermal imaging are affected by a number of external factors and may not always reveal hidden and trapped moisture [23, 24]. Therefore, we designed a climbing mode to addresses these limitations.

In climbing mode, we will scan along a building elevation with the use of microwave based GPR, since such a sensor must be in physical contact with the building surface for defect detection. Microwave-based GPR and through wall imaging technology is routinely deployed in the construction and building space to detect underground pipes and utility lines and embedded rebar within concrete members [25, 26, 27, 28, 29]. Microwave-based grid scans over a building will yield a baseline pattern that accounts for the underlying structure. All grid scans will then be compared to the baseline to find anomalies, such as trapped moisture.

We preset these two control algorithms in the flight controller. When we need to switch to climb mode, we need to remove the front RGBD camera, connect the power cable, and replace the bottom thermal camera with a GPR sensor. Meanwhile, we will switch to the climb mode in the control tablet.

Onboard Sensors. To effectively assess a building we will need to capture environmental data using a number of sensors. Our solution will capture RGB data, thermal data, depth data, and long-wave/microwave radar data. RGB data will be captured with depth data simultaneously by Intel Realsense D435 RGBD camera [30]. In those indoor environments, the Intel Realsense L515 Lidar [31] will replace Intel D435 RGBD camera and provide more accurate and dense depth data. Thermal data will be recorded by an FLIR C3-X camera [32] and attach on the bottom of the drone. FLIR C3-X is a portable thermal camera that could provide thermal information and RGB information at the same time. Proceq GP8800, a ultra-portable GPR sensor [33], will be installed on the bottom port and use for capturing long-wave/microwave radar data.

5 Software Algorithm

To achieve fully automatic defect detection and flight control, we plan to use the state-of-art and well-developed machine learning algorithms. These algorithms include drone adaptive control, data visualization, abnormal detection and 3D reconstruction. The following are the details of the algorithm that we are going to use in the prototype.

Adaptive Control. To avoid unexpected obstacles and fly the designated route, we will use an adaptive control algorithm to control our drone robot. Model Reference Adaptive Control (MRAC) [34] is the most common adaptive controller in recent years. Compared with the fixed-gain approach, it can enable safer and quicker drone landings when its actuator fails. We use MRAC instead of Self-Tuning Control System (STC) [35] because the MRAC drone flight control model is easier to formulate, especially given its well-developed status within the drone research community. Compared to previous work, our drone has added a wall climbing mode. We plan to extend the direct MRAC to the climbing control of drone, especially for the angle control of the motor shaft.

Thermal Anomaly Detection. Thermal cameras have been widely used in energy inspection for building envelopes. Our solution features the large-scale energy inspection via onboard thermal camera. Since the output of FLIR C3-X is already a color code image, we only need to find those abnormal colors in the bounding box, whether is dark cold blue or hot red. Due to the different thermal conductivity of materials, we plan to use contour detection to exclude those false positive results. Once the screening is completed, we will record the coordinates of the abnormal color patterns for further inspection.

Radar Wave Visualization. If any problems are detected in the camera survey, we will perform finer-scale moisture inspection. In the building space, microwaves have been extensively used for detection and analysis. GPR and through wall imaging radar use microwaves to detect covered and buried objects. Microwave-based radar has been used extensively to find buried pipes and rebar embedded in concrete. Pipe and rebar detection works by establishing a baseline microwave reflectance signal and searching for differences from that baseline. Based on this principle, microwave-based radar has also been used for detecting moisture in building components. Through more complex signal analysis, it has been extended to tracking people behind walls and extracting internal structure of a wall assembly itself.

In our previous work, we developed learning-based radar wave visualization [36]. This algorithm was originally used to detect objects and estimate poses through the wall. If we use this algorithm in building envelope moisture detection, we need some additional preparations. First, we need to collect the water leakage data of building envelope. In the original paper, the author trained a Convolutional Neural Network (CNN) to visualize the radar images. In our prototype, we will replace the RGB data with thermal images and numerical data from moisture meter. This algorithm will provide us a three-dimensional thermal data instead of 2D thermal images.

3D Reconstruction, Mapping, and Visualization. In order to accurately and effectively convey the size, scope, and location of an issue, building envelope issues will be overlaid onto a digital twin of the site being inspected. This digital twin will be created through image-based SfM, VSLAM and depth data [37]. VSLAM will give us a specific 6 degree-of-freedom pose that will allow us to know how all the images, RGB or thermal, relate to each other. Using SfM, we can piece these images together to create 3D color and thermal digital twins of the inspection site. Depth data can provide additional surety of shape and structure of the inspection site. All of this data can be rectified and combined to produce a point cloud of data. This point cloud will allow a human or AI reviewer to easily understand the location, scale, quantity and type of damage. We will also employ additional techniques to aid in 3D reconstruction and visualization. We will use our patented point-plane SLAM algorithm to perform highly accurate 3D mapping of an indoor structure using our RGB and depth data [38]. We will also use our DeepMapping algorithm which enables fully automated indoor 3D mapping without human attendance [39]. These mapping methods will use machine learning to create a detailed and accurate 3D map of the inspected building envelope.

Augmented Reality and Retrofits. After a 3D thermal map has been created that shows the size, location, scope, and type of building envelope issues, this information can be used to aid envelope retrofit projects. Augmented reality (AR) can help inspectors understand the location and size of building envelope failures much more effectively. We can achieve glassless AR by using our smartphone or tablet included in the robot toolbox. This will allow us to directly show the virtual 3D information with camera images on the screen. This greatly reduces the technical and experience requirements for inspectors, such as understanding complicated radar images.

6 Conclusion and Future Work

qThis paper proposed a robotic toolkit and software pipeline that could rapidly diagnose, quantify, and locate building envelope issues. Our two mode tethered quadcopter drone has a variety of environmental sensors that can be used to capture RGB, thermal, microwave, depth, and pose data. This data is then sent into the software pipeline where it is processed to find, classify, and quantify building envelope issues. These issues are then overlaid onto a digital point cloud twin. At this stage, if it is visualized to a building inspector, they will be able to easily understand the location, scale, quantity, and failure type. Additionally, they will be able to use this knowledge to develop a location specific scope of work for building repair or retrofits.

End-User Benefits. Ultimately, this envelope inspection pipeline has two major benefits for its users. By automating the inspection process, we reduce the time and domain knowledge required to carry out an inspection. This could enable people to carry out inspections more often, allowing a more consistent monitoring of building envelope conditions. Secondly, we clearly visualize the location, size, and type of envelope problem so that decisions on repairs can be data driven and proactive instead of reactionary and complaint driven. We believe that building scientists and property managers will benefit from this toolkit for performing robust high-level inspections cheaply, quickly, and routinely.

Future Work. Our future work will focus on making prototypes that can achieve all of the above-mentioned functions We will also develop our own algorithm for the thermal anomaly detection and wall climbing control. The conceptual design we present here lays the groundwork for future testing of hardware prototype and defect detection algorithms on small-scale envelope section mockups and real buildings for inspection speed and detection accuracy. Overall, we believe that our work can provide a safer environment for inspectors and reduce the technology and experience requirements for inspectors.

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