Autonomous Mobile Robot for Installing Blown-In Insulation

Brice Diomande, Chris Lee, Henry Licht
University of Pennsylvania, in partnership with Saint Gobain CertainTeed

Project Objective

This project demonstrates proof of concept for the use of mobile robots to install **blown-in insulation** in a **laboratory or attic-like environment**. Blown insulation is installed by filling indicated cavities with loose fill fiberglass dispersed by a blowing machine. This process is tedious and involves prolonged **exposure to airborne particles** for human operators. Our sponsor, Saint Gobain CertainTeed, sought to understand whether a robot could assume the **role of the hose operator** in this process.

The proposed solution emphasises the following sponsor priorities:

- Continuous operation with minimal human involvement
- Identification and execution of high-confidence standard tasks

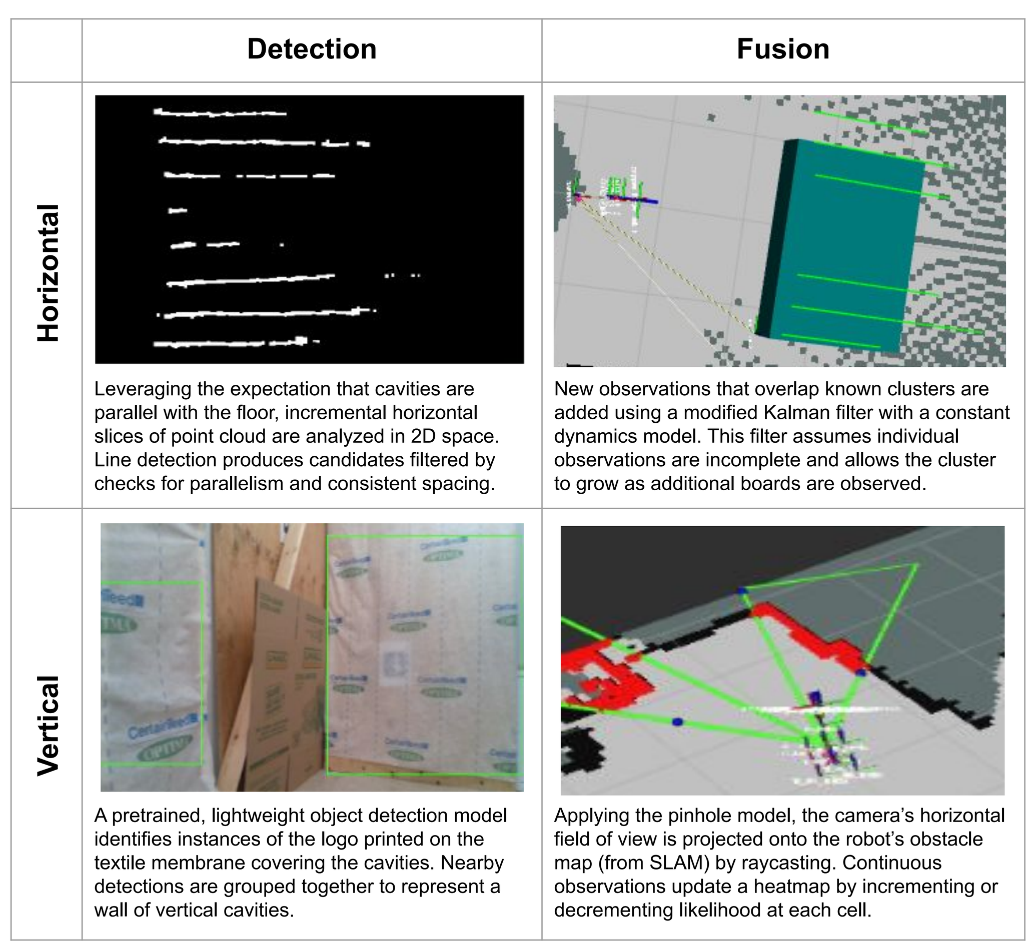
With this in mind we focused our efforts on two particular use cases:

Horizontal Blowing Ground-level cavities created by rows of floor joists, filled to a consistent and prescribed thickness.

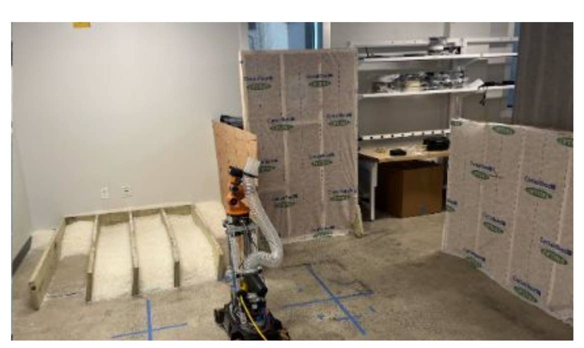
Vertical Blowing Blowing insulation into wall between studs, past a sheer textile membrane, to achieve a desired consistent density.

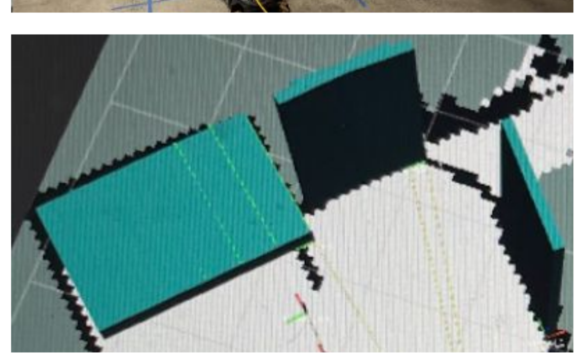
Candidate Cavity Detection

While exploring the space the robot detects patterns indicating clusters of cavities. Observations are aggregated and cross-associated to generate a semantic map of the scene which accurately positions the detected clusters in space.



Outcome
Navigated by teleoperation, the robot produces stable pose estimates for all cavities in our lab setup and measures cavity dimensions accurately within 3%.

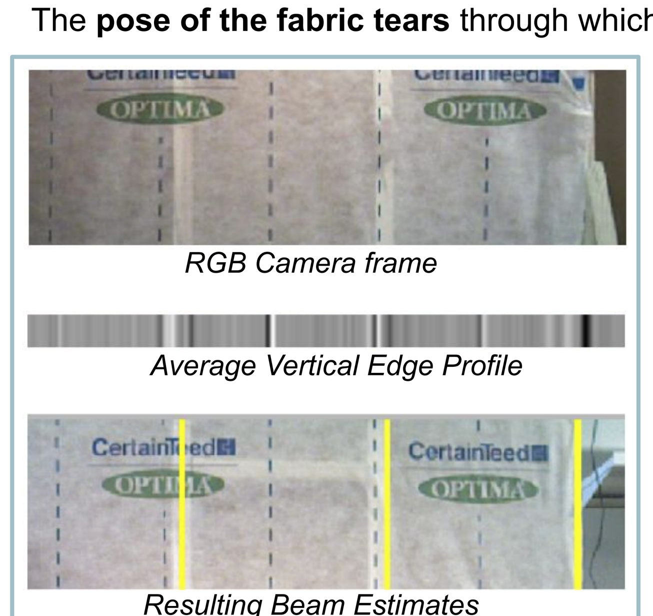




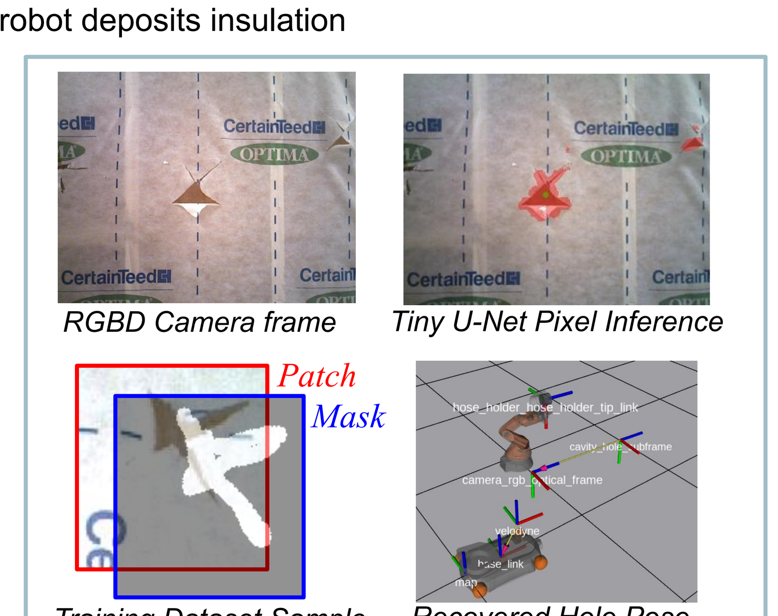
Vertical Cavity Detection

As opposite to the horizontal cavities, the vertical cavities demand precise knowledge of their structure to complete the task at hand. Specialized pipelines are therefore used to accurately estimate:

- The **position of the vertical beams** which delimit each cavity
- The **pose of the fabric tears** through which the robot deposits insulation



Beam detection through semi-opaque cover



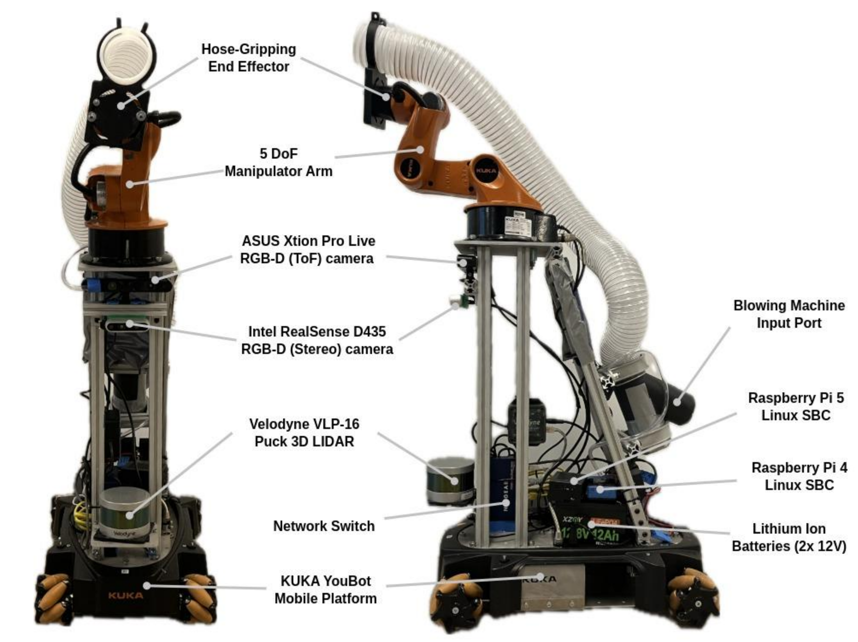
Cavity Hole Localization

Hardware Overview

Our prototype is based on the KUKA Youbot, a research platform consisting of a mobile base with a mountable 5 DoF arm. This platform provides us the ability to traverse a space and also perform hose manipulations such as in the vertical blowing use case.

We made the following modifications to the Youbot to support our application:

- **Physical enhancements:** A support rig to elevate the arm to waist height, and various hose mounting attachments to provide an interface for a blowing machine.
- **Computing enhancements:** Two Raspberry Pis to compensate for limited compute on the YouBot, and a network switch to reduce latency for the distributed system.
- **Sensing enhancements:** A 3D Lidar Puck for accurate localization and mapping, and a RGB-D camera for use in detection tasks.



Physical Robot with Labeled Components

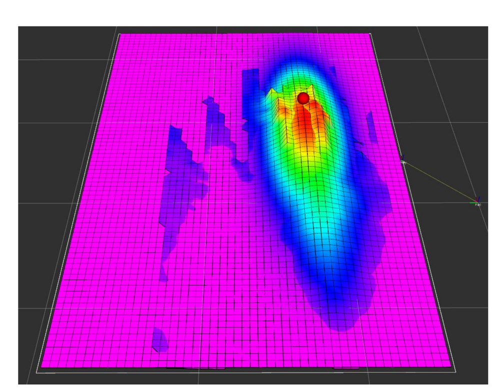
Insulation Delivery Modelling

The insulation deposition rate is modeled as a 2D gaussian distribution. A series of overlapping gaussians would approach a near uniform fill height near the center of the cavity.

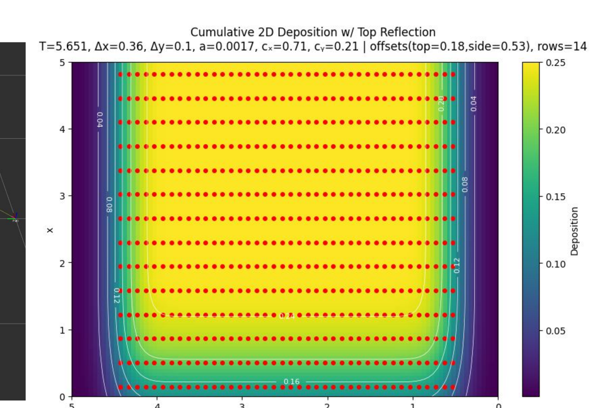
$$v = \frac{2\pi a \sigma_y \sigma_x}{F_{target}\Delta x} \quad \text{(Continuous; constant velocity)}$$

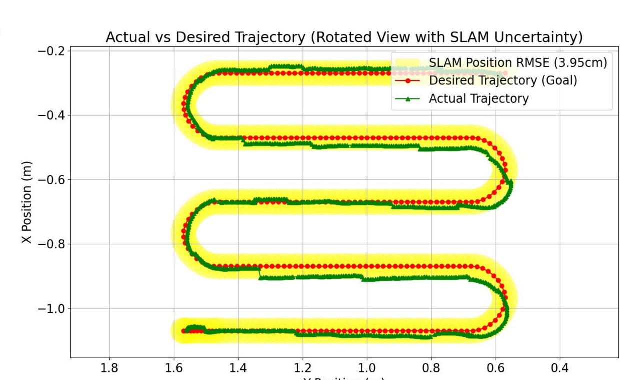
The gaussian parameters are determined by curve fitting the elevation map of deposited insulation, and these parameters are used to derive the ideal velocity profile or stall times to achieve a consistent specified fill height.

$$T = \frac{F_{target}\Delta x \Delta y}{2\pi a \sigma_y \sigma_x} \quad \text{(Discrete; stop-and-go)}$$



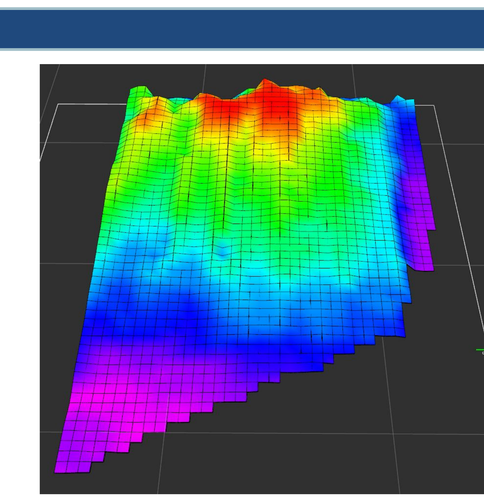
Actual elevation map and 2D gaussian fit overlay



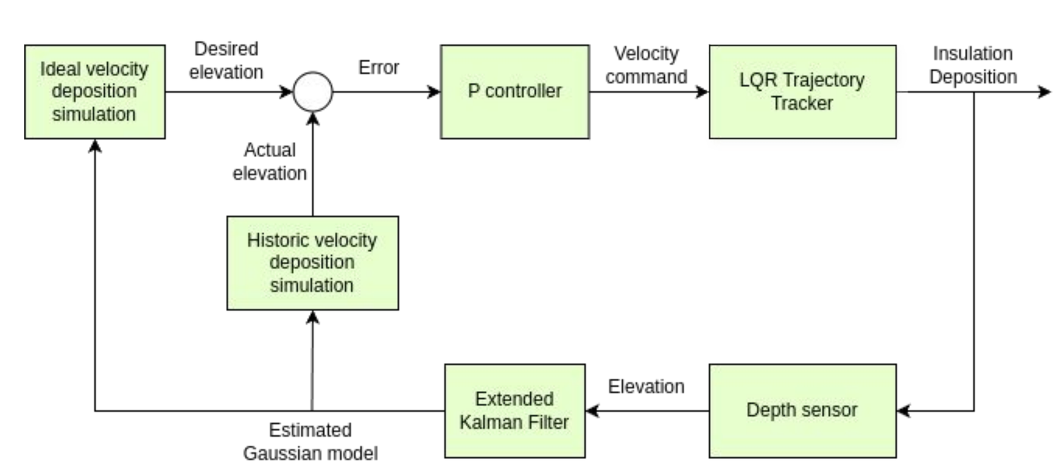


Monitoring Insulation Accumulation

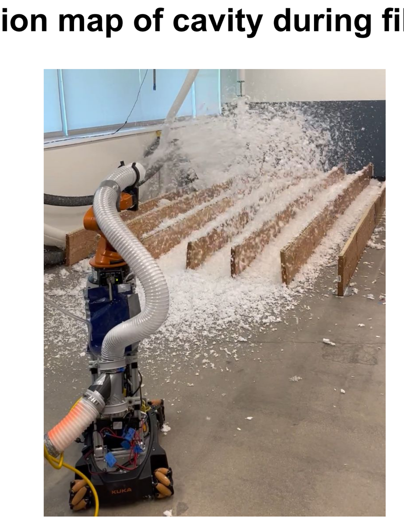
We use a depth sensor to monitor the insulation fill height and an extended Kalman filter to update the gaussian parameter estimates. Using the updated gaussian parameters, we compare the simulated fill height using ideal velocity to the simulated fill height using historic velocities. The difference in fill height is used to update the robot velocity.



Elevation map of cavity during filling



Closed loop control of insulation filling



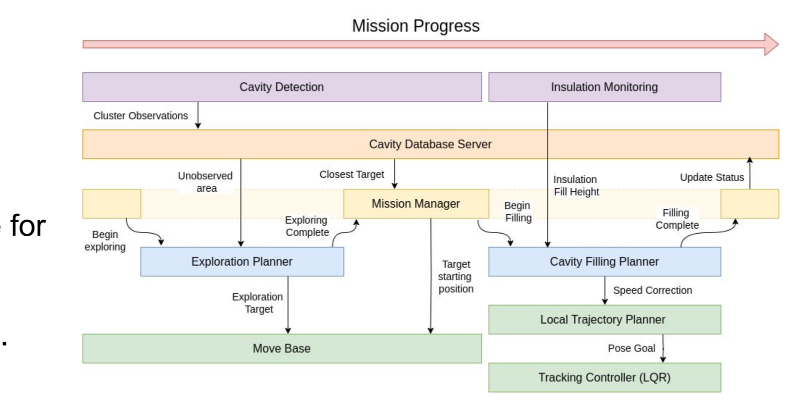
Horizontal Blowing Test

Software Design

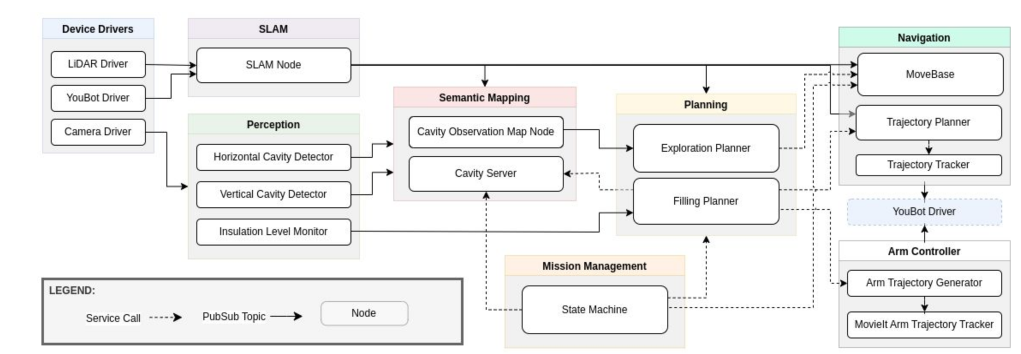
The robot's execution logic includes three states:

1. **Exploration:** Navigate and process detections until all reachable area has been observed.
2. **Target Acquisition:** Query the cavity database for the nearest target and navigate to tit.
3. **Target Filling:** Plan and track a trajectory to ensure coverage of the target while monitoring .

State transitions are managed by a central state machine node which delegates state logic to planners.



Process and Information Flow

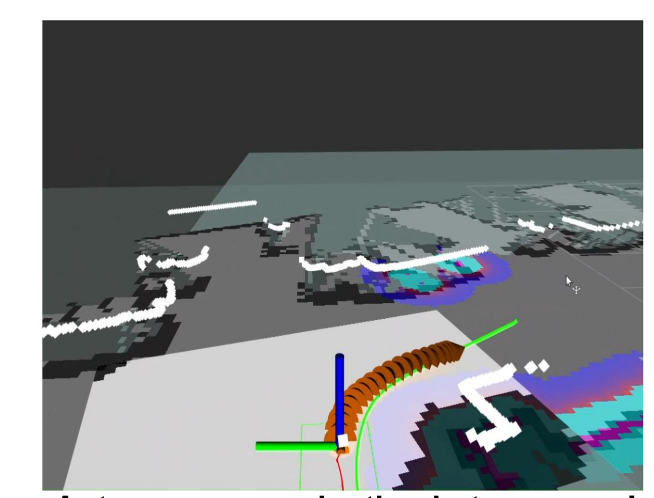


ROS Architecture Diagram

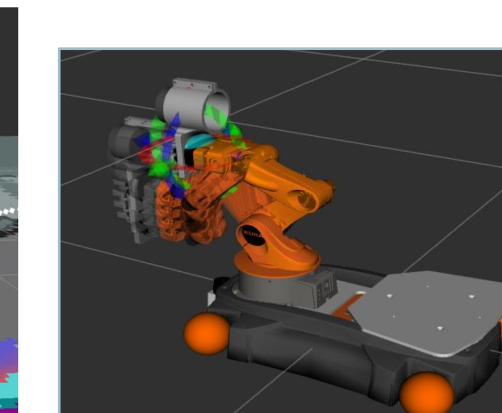
The robot software is structured as a network of nodes which coordinate and share data with each other within ROS. We utilize parts of the ROS framework including topics services, actions, and standard message types as well as our own custom messages.

SLAM, Navigation and Manipulation

Map Generated by SLAM Module



Autonomous navigation between goal and obstacle avoidance



Arm trajectory generation and tracking

ROS1 frameworks such as SLAM_toolbox, Move_base and Moveit considerably helped reduce the overhead necessary to achieve the above core capabilities by abstracting the implementation details of the various algorithms chosen to

Future Work

Improving Exploration Strategy

- In addition to ensuring complete coverage, the exploration process should encourage further investigation of regions where cavities are observed, leveraging our existing cavity observation heatmap.

Extending to Realistic Attic Environments

- The robot must recognize surfaces safe to drive on, level floors cannot be assumed
- Realistically the robot will not have enough space behind it to allow the calculated trajectory S-shaped trajectory. We will need to map different hose orientations and feeder pressures to insulation fill rate model.

Insulation Deposition and Monitoring

- Skewed gaussian model for the insulation fill rate along with numerical simulations to determine fill parameters.
- Use RGB instead of depth for insulation level monitoring to get a larger sensing region.

Acknowledgements: Thanks to our sponsor Dr. Pierre Lombard and his team at Saint Gobain, especially Gene Wheeler, for being engaged and accommodating throughout the project term. Thanks also to Jeremy Wang and Britny Major of the PERCH Design and Fabrication Facility for helping us build our prototype. Lastly, thank you to our advisors Dr. M. Ani Hsei and Dr. Eric Eaton for your guidance and support. .