# Sensing and Sampling of Trace Contaminations by a Dexterous Hexrotor UAV at Nuclear Facilities - 18600

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**ABSTRACT**
Safe and efficient cleanups are a priority for decontamination and decommissioning of nuclear facilities. The contaminations of byproducts and wastes in such nuclear facilities pose a serious problems while decommissioning, to both the operators and public. Sensing these contaminations and cleaning them is an essential part of the safety procedures. The contaminations might range from low-energy to high-energy byproducts. Sensing these byproducts would require contact based or non-contact based sensing, based on its energy levels. Byproducts such as americium, are low-energy which makes it difficult to sense and sample without contact. Therefore, the workers need to physically swab the surfaces to collect the samples of these contaminations. These tasks pose a great danger for the safety of the human workers which includes the risk to reach greater heights, exposure to the radiation and sampling the entire building. A robotic solution is much more desirable in these cases, where the worker can safely handle the contaminations from a safe area. Use of robotic technologies inside these hazardous environments ensures the safety and enhances the performance.

The more suitable robotic solution for reaching great heights and covering large areas of nuclear facilities, are aerial vehicles. Multirotor unmanned aerial vehicle (UAV) are chosen for their ability to hover at a position and also fly around in confined spaces. Quadrotors are a common choice of multirotor UAVs both research and industry because of its ease to fly and commercial availability. For the applications during the cleanups we need the UAV to not only hover and fly in confined spaces, but also interact with the physical world. Despite of quadrotor's advantages, they are not a best suit as they can't interact with the physical world. The tasks involving physical interactions would require the UAV to apply arbitrary forces & torques in all six degrees of freedom (DOF). As quadrotors are under-actuated and non-holonomic in motion, they cannot exert all the required forces. At Collaborative Robotics Lab, Purdue University, we developed a novel multirotor UAV solution, Dexterous Hexrotor, which can exert arbitrary forces & torques in all six DOF, independently and instantaneously. This enables the UAV platform to quickly respond to the external disturbances and precisely hold its position during the mission.

The Dexterous Hexrotor serves as a robotic tool for the workers to perform sensing and sampling during the cleanups. Workers can operate Dexterous Hexrotor manually and/or semi-autonomously with human intervention. Manual control requires the worker to fly the Dexterous Hexrotor using a remote control. So the workers should possess knowledge on flying the UAV and to perform physical interaction. A semi-autonomous Dexterous Hexrotor requires human input to some extent and requires very less knowledge of flying. The autonomy is designed to operate in flight mode and sampling mode. In flight mode, Dexterous Hexrotor takes off from a "safe" area, reaches the desired altitude, and fly autonomously towards a sampling point. This sampling point is the target position specified on the 2D reference map. This mode also includes navigation towards the sampling point, avoiding the obstacles in the constrained environment. After reaching a stopping point, Dexterous Hexrotor waits for the human input for a target location to swab and collect samples. The Dexterous hexrotor is now in sampling mode and waits for the human input. The human operator selects the swabbing location through the live streaming video from onboard camera.

Through visual servoing, aided by the map, the UAV will move closer towards the target position. It then transitions to the impact control scheme to perform physical interaction with the wall and collects samples. Once the sample is collected, it autonomously returns back to the takeoff position in "safe" area for the analysis by mass spectrometry. In this paper, we majorly focus on the physical interaction strategy and the required components which enables the autonomy.

Decommissioning of nuclear facilities requires decontamination inside the entire buildings. Decontamination of nuclear facilities involves sensing and sampling the huge buildings, long shafts, etc. Sampling the entire facility is not possible due to the limitation in Dexterous Hexrotor's flight time. But this can be achieved by using a swarm of Dexterous Hexrotors to cover larger areas. The onboard robotic arm can be designed based on the applications such as cleaning, applying sealants, etc. The modularity of the design allows us to switch components as per the requirements of the task. These kind of robotic solutions functioning as tools for the workers, aims to make the work environment safer and playful.

## INTRODUCTION

Managing the nuclear waste from nuclear power plants and nuclear weapons development has been a major issues over the decades. Several facilities containing the nuclear reactors, chemical processing buildings, laboratories are involved in this process. The nuclear wastes from such facilities are processed in processing facilities and are stored in underground storage facilities. Many of such facilities are set for decontamination and decommissioning and some facilities would require constant inspections for contaminations.

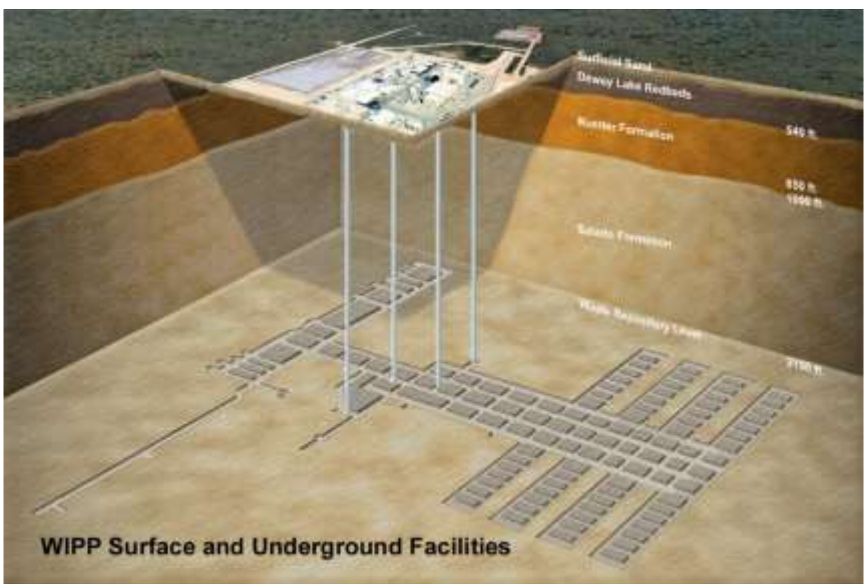


Fig. 1. Carlsbad Waste Isolation pilot plant (WIPP)

The Department of Energy and the office of Environmental Management has being assigned to perform nuclear waste cleanups in 107 sites across the United States. There are still 16 active sites which are yet to be cleaned up [1]. These active sites include Savannah River site, Hanford site, Portsmouth Gaseous diffusion plant, Sandia National Laboratories, Carlsbad- WIPP, etc. The Carlsbad –WIPP is a permanent storage facility for Transuranic (TRU) radioactive waste which contains alpha-emitting isotopes with an atomic number greater than uranium.

The facility occupies a space of 16 square miles at 2150 feet underground. Vertical shafts circulate air from the surface as shown in fig 1. Performing cleanup tasks safely in such facilities is not an easy task for humans. Especially the vertical shaft pose a serious challenge for inspection in terms of reachability and sensing. Savannah River site and Hanford site has facilities such as reactor building, support facilities, auxiliary structures, etc., which need regular cleanups. DOE has signed up to decontamination and decommission (D&D) 415 facilities and structures at Portsmouth site where uranium enrichment operations were held. Demolition of 36 inactive facilities and building larger than 700,000 square feet has been accomplished by safely eliminating the contaminations. An aerial view of Portsmouth gaseous diffusion plant is shown in fig 2.

Fig. 2. Portsmouth Gaseous Diffusion Plant

The nuclear sites mentioned above, always poses safety hazard for the workers and also to the general public. Considering the harsh environment in such facilities, it is safer to use robots to assist humans rather than sending humans. Robots have been an integral part of some of the cleanups, D&D activities. Most of these robots have been developed to perform a specific task, at specific locations. This doesn’t yield an efficient approach for robotic solutions towards the existing problems, as it requires time and resources to build newer robots. Modular design is much desirable to yield efficiency in serving multiple purposes by reconfiguration. Mothership is one such ground robot, designed to serve multiple purposes because of its ease of configurability [2]. It is built in a modular fashion which allows the engineers to create a new robot from the same modules depending on the tasks and terrains. Another important factor to be considered in developing a robot is the ease to control them. The workers on site should be able to control the robot rather than a highly paid engineers. These two factors provides an effective robot which acts as a tools for the workers to enhance their tasks performance in D&D.

## DEXTEROUS HEXROTOR FOR SENSING AND SAMPLING

We propose Dexterous Hexrotor as a tool for the workers in nuclear facilities to perform their job tasks with safety and efficiency. The tasks would require the UAVs to cover the large facilities and physically interact with the contaminated surfaces to collect samples and perform cleanups. Commercially available multirotor UAVs have the ability to hover and fly in confined spaces by avoiding obstacles. But they can’t physically interact with the contaminated locations.

Dexterous Hexrotor is capable of flying in confined spaces and physically interact with surfaces to collect samples or perform cleanups, autonomously [3] [4]. Dexterous Hexrotor is built from a hexrotor platform with propellers tilted at an optimized angle, called *cant*. Common multirotor UAVs such as quadrotor, have parallel actuators which enables the actuation in 4 DOF. The remaining 2 DOF, which are forces in horizontal plane, are achieved through torques around horizontal axes. This makes the UAV under actuated, non-holonomic and not suitable for physical interactions or flying close to the physical structures. The *cant* angle in Dexterous Hexrotor enables forces and torques in all six DOF independently, providing instantaneous forces in the horizontal plane. The Dexterous Hexrotor is capable to fight external disturbances during the physical interactions and also disturbances associated with flying close to the structures [5].

**Dexterous Hexrotor Prototypes**

A team of Dexterous Hexrotors are developed to perform the operations autonomously. Each Dexterous Hexrotor is configured according to the requirement of the task. A 1 DOF Robotic arm is installed on the UAV to perform physical interactions. For an autonomous sampling task, there are two different configurations, one for mapping the workspace and the other for physical interactions as shown in fig 3.

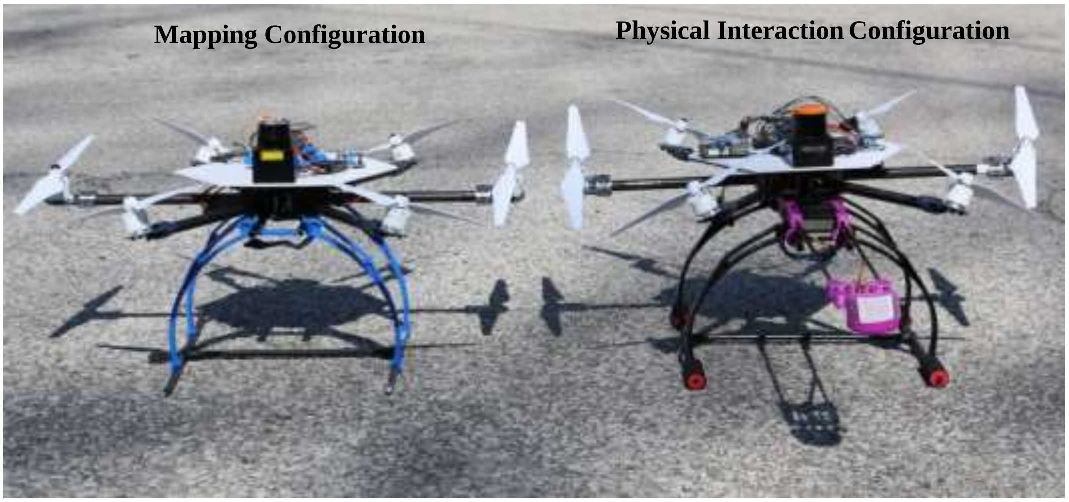


Fig. 3. Dexterous Hexrotor prototypes, one in mapping configuration and the other in Physical Interaction Configuration

The Dexterous Hexrotor configured for mapping is required to be flown manually by the operator, this is a one time task. A reference map out of laser sensor data is developed and used for autonomous flight. The Dexterous Hexrotor configured for physical sampling is primarily designed for autonomously flyinh and interaction with the environment. The hardware and software components on same on both the configurations and are presented below.

<u>Software Design</u>

The software architecture employed in autonomous Dexterous Hexrotor has two stages of computation. The first stage has the low level computations of the UAV flight Control, trajectory estimation and control law for physical interaction with the environment. This is mostly done inside the RecoNode [6]. The RecoNode has the autopilot controller for attitude and altitude control, sensor data is processed to estimate UAV state and control the actuators.

The low level programming is done in C with real time operating system PBORT. In the second stage, the high level computations are achieved using Nvidia® Jetson™ TX2, which is a Linux microcomputer. It enables to program SLAM in Robot Operating System (ROS) and Visual servoing in Open Source Computer Vision library (OpenCV). The position feedback and trajectory commands from TX2 are sent to the RecoNode, which in turn enables the RecoNode to send control commands for the UAV flight and physical interactions.

Hardware Design

The Dexterous Hexrotor is designed to have dedicated onboard sensing and computing. Each UAV has rotor system, sensing system, the controllers as shown in fig.3. This forms a basic hardware configuration for both mapping and physical interactions. A simple comparison between the mapping configuration and physical interaction configuration of Dexterous Hexrotor is given in table I. The Dexterous Hexrotor in physical interactions configuration has additional set of sensors, a robotic arm with sampling mechanism and different rotor configurations compared to mapping configuration. The rotor configuration, *cant* angle, is significant for a specific task. The mapping task would require the Dexterous Hexrotor to fly holonomic in plane while generating the reference map. So the *cant* angle is set to a configuration where it just needs to exert forces in horizontal plane to move. The physical interaction task would require more than just holonomic movement in the plane, it needs to exert horizontal forces sufficient for the robotic arm onboard to make a contact, yet maintain the hover without losing the altitude. Thus, the *cant* angle of Dexterous Hexrotor is optimized based on the task it is being used.

TABLE I. Comparison between the mapping configuration and physical interaction configuration

| Property | Mapping configuration | Physical Interaction configuration |
|---|---|---|
| Rotor Configuration (*cant*) | $18^0$ | $28^0$ |
| Robotic arm with sampling mechanism | No | Yes |
| Autonomy | No | Yes |

The system architecture in fig 4, includes onboard controllers which comprises of embedded Linux microcomputer and a FPGA based microprocessor. RecoNode is the multi-processor architecture based on Virtex 4 FPGA with multiple, hardcore PowerPCs developed in Collaborative Robotics Lab (CRL) [7] [8]. It is used to control the actuators, operations of the sensors and interactions with the environment. Jetson™ TX2 is the Linux microcomputer is used for perception of the environment using the sensors. It is installed with OpenCV and ROS.

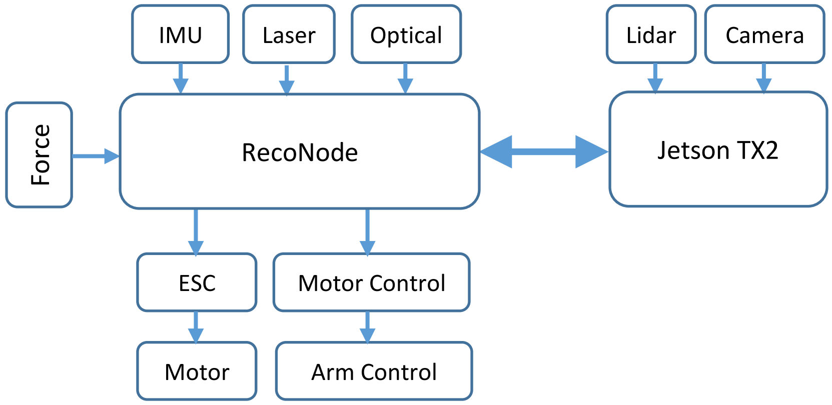


Fig. 4. System Architecture employed in autonomous Dexterous Hexrotor.

Different sensors are employed in Dexterous Hexrotor to enable the autonomy and physical interaction, as depicted in fig 5. They are categorized into two types, one set of sensors are for UAV state estimation and another set of sensor are to perceive the environment. For UAV state estimation, there is an IMU sensor to measure the attitude, a laser range finder and pressure sensor to measure the altitude, an optical flow sensor for velocity feedback with respect to ground. Both the laser range finder and optical flow sensor are down facing. To perceive the environment, the UAV is equipped with 2D Lidar and an onboard Camera. The Hokuyo URG-20LX is a 20m range Lidar sensor, used to generate a 2D map from the laser scans. This enables simultaneous localization and mapping (SLAM) using the ROS environment. The camera onboard provides live video streaming and enables Visual servoing using sift features in OpenCV, to perform physical interactions at the desired locations.

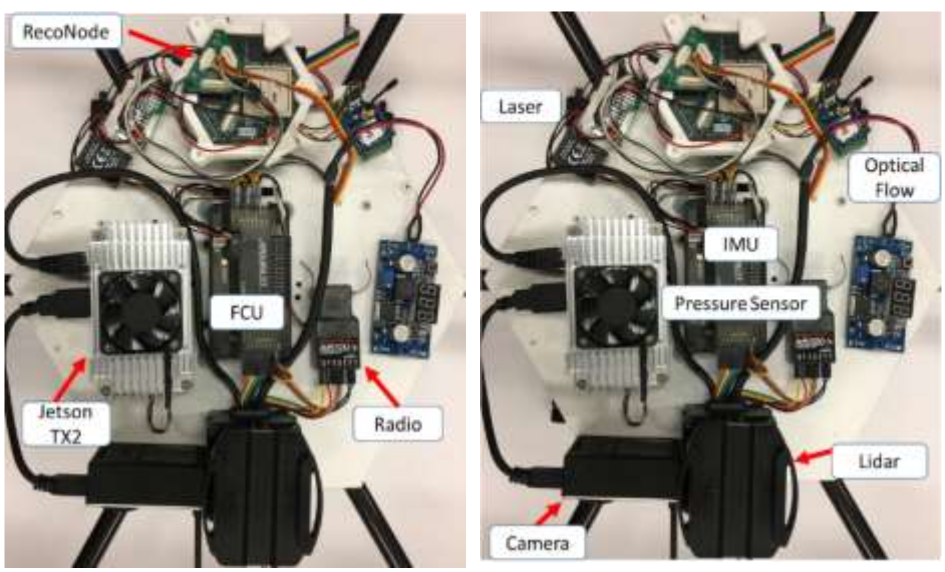


Fig. 5. The electronics and onboard sensors required to fly Dexterous Hexrotor Autonomously.

Physical interactions are achieved by the onboard robotic arm with a sampling mechanism. The robotic arm is a simple rigid arm with reel-to-reel sampling mechanism shown in fig. 6. The reels are driven by a small DC motor connected to one of the reels.

The sampling plate makes a smooth contact with a surface using force feedback control. Then by rolling the reels, the sampling materials collects the samples. For cleaning the contaminated surfaces, similar type of sampling mechanism can be used with a cleaning material on the reels. The mechanism can also be replaced with a small gun which can apply sealants at desired locations. In general, the sampling mechanism can be replaced with any type of physically interacting mechanism with respect to the tasks.

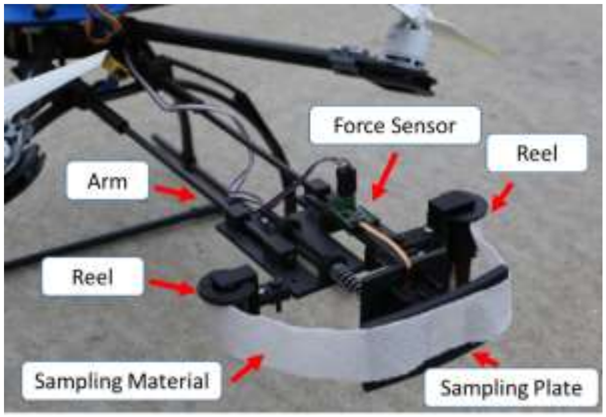


Fig. 6. Sampling arm mechanism for physical interaction with the surfaces with an attached force sensor.

**Physical Interaction Strategy**

Physical interactions are required to be performed in a controlled fashion, due to the risk of reaction forces. A physical interaction strategy is critical in enabling a smooth interaction with the vertical surfaces. A hybrid control strategy shown in fig. 7, has two control modes for interactions, which are unconstrained position control and constrained force control [9]. The position control is enabled during the flight through the free spaces. The force control is enabled to exert specific amount of force onto the vertical surface to maintain a contact for interactions.

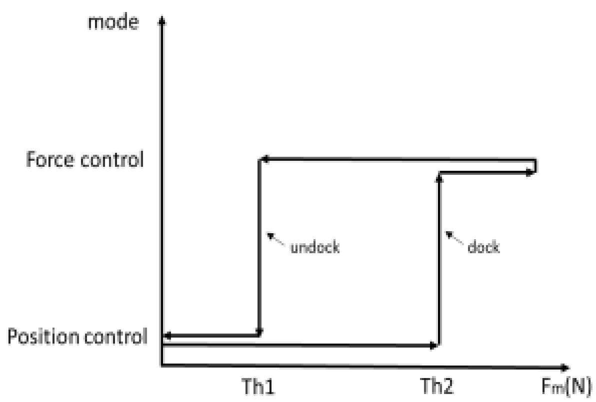


Fig. 7. Control strategy switching the position control and force control modes.

The Dexterous Hexrotor in position control to fly in free space until it reaches the target location, eg, wall, or crane rail, etc. The control mode is then switched to dock mode which enables the constrained force control. The UAV then makes a slow approach towards the target location and engages the physical contact with a contact force.

With an undock command, the control mode switches back to position control with lower force thresholds (Th1). The impact with the surface poses problems while switching from position control mode to the force control mode. The force controller provides active damping to stabilize the impact forces and maintain a steady contact. The sampling mechanism shown in fig 6 has mechanical compliance to dampen the energies associated with impact.

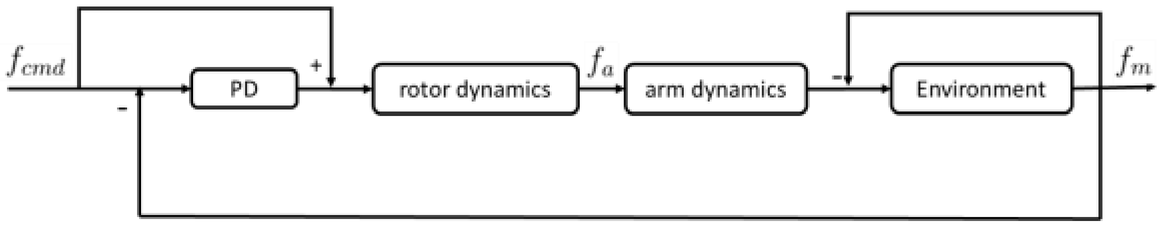


Fig. 8. Block diagram of force controller with Proportional gain and force feedforward

A PD controller with negative gain and force feedback is designed as the force controller for a steady impact as shown in fig 8. The measured force, $f_m$, being applied while making a contact is feedback to generate a negative gain using the force input, $f_{cmd}$, which dampens the reaction forces and ensures a firm contact with the surface.

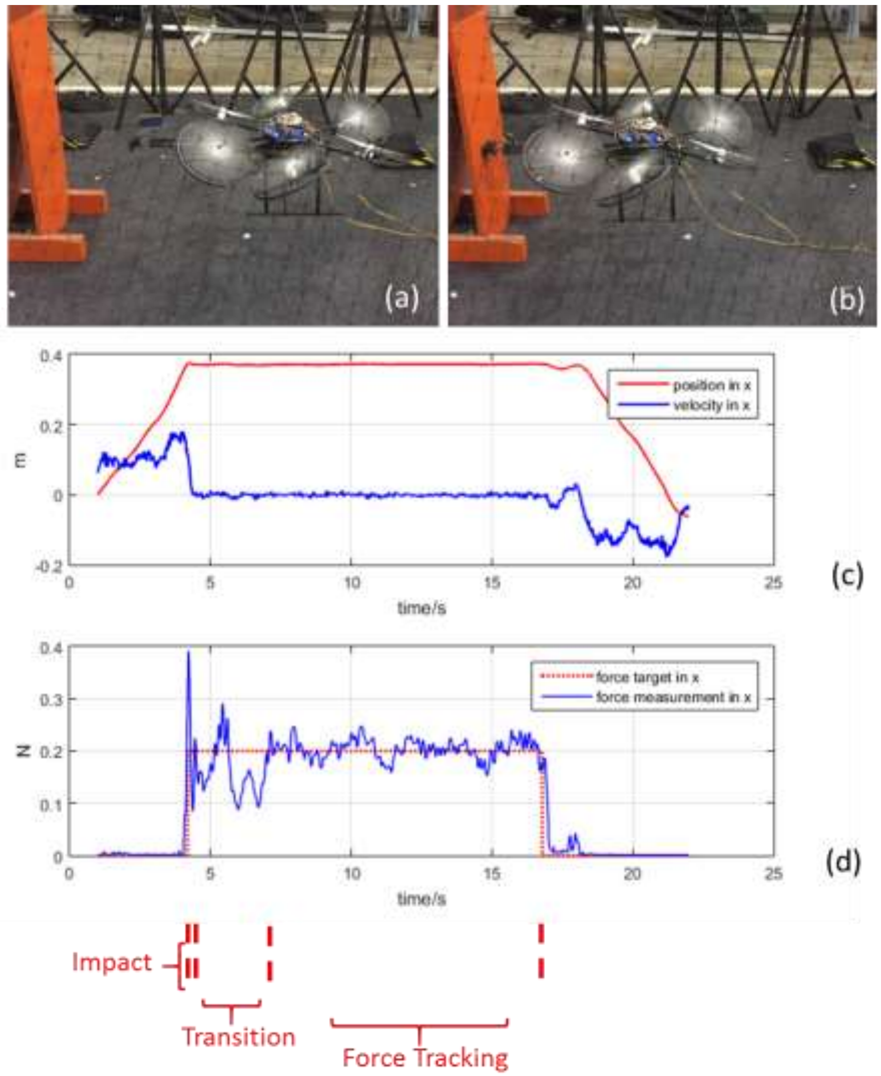


Fig. 9. Experiment to validate the Physical Interaction strategy (a) Dexterous Hexrotor at hover in position control mode (b) Dexterous Hexrotor in force control mode while making a contact (c) Position and Velocity while making a contact with the surface (c) Measured force, $f_m$, during the mission.

We conducted an experiment to validate the interaction strategy and measure the response of the controller. The experiment starts at hover near a vertical surface, fig. 9 (a), and approaches the surface at a speed of 0.2m/s, fig. 9 (b). Once the contact is established, the impact phase is about 0.2s. A target force of 1N is tracked for 10s and then switches back to the position control. The standard deviation of the constant force being applied during the interaction is around 0.2N. The graphs in fig. 9 (c) & (d) shows the smooth interactions with the vertical surfaces and can be scalable for different physical interaction applications.

**ONBOARD AUTONOMY FOR DEXTEROUS HEXROTOR**

The ultimate goal is to fly and perform physically interactions autonomously with very less human intervention. This paper is an initial step towards developing a fully autonomous Dexterous Hexrotor. One of the most important issues is the complexity of the usage of Dexterous Hexrotor. The reason for having an autonomous Dexterous Hexrotor is to release the burden on the operator to fly or controlling the robots. The autonomous Dexterous Hexrotor still requires human inputs through a very simple user interface, to accomplish a task effectively. Employing a Dexterous Hexrotor will not replace workers, instead it involves the operator in performing a tasks from safe area. With that being said, this section presents the autonomy that we aim to achieve on Dexterous Hexrotor and the parts of autonomy that have been physically tested.

The onboard sensors discussed in the previous section provides the data required for autonomy. These sensors are used for different purposes for two configurations of Dexterous Hexrotor. In the mapping configuration, the 2D Lidar data is used to generate a grid map using hector SLAM in ROS. This map is used as reference map for autonomous flight and is shared among all the UAVs. A 2D map of the demo workspace room at Purdue University is shown in fig. 10. As generating a map is onetime process, we can fly the Dexterous Hexrotor in manual mode or semi-autonomous mode. The physical interaction configuration is used for autonomously flying and physical interactions. The 2D Lidar data in this configuration will be used for localization and navigation using the reference map.

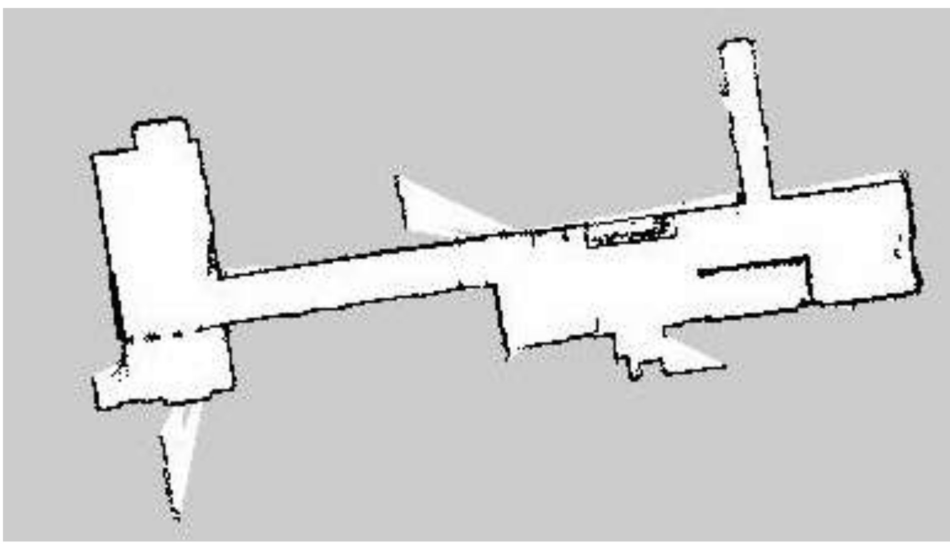

Fig. 10. 2D map from the Lidar scans of an indoor workspace.

The additional sensors used for an indoor flight are the 1D laser sensor and the optical flow sensor pointing downwards, as mentioned in the hardware section. The 1D laser sensor is used for tracking the altitude of the UAV and hold it at a specific altitude. This is very important for a successful autonomous flight, as the reference map is build out of 2D lidar data at a specific altitude. If the UAV is not able to hold its altitude then it can’t localize itself on the map and navigate around. Therefore, it is very crucial to hold the altitude throughout the mission. The optical flow sensor provides the velocity feedback in reference to the ground, and acts as a redundant sensor for IMU.

Physical interaction at a specified target location can be achieved through visual servoing and force control. The live streaming from the onboard camera can be used to select the point of interest where physical interaction is required. The physical interaction strategy in Dexterous Hexrotor enables the interaction using force feedback controller as shown in fig. 11. After finishing the task, the Dexterous Hexrotor is expected to return to the base by localizing and navigating autonomously.

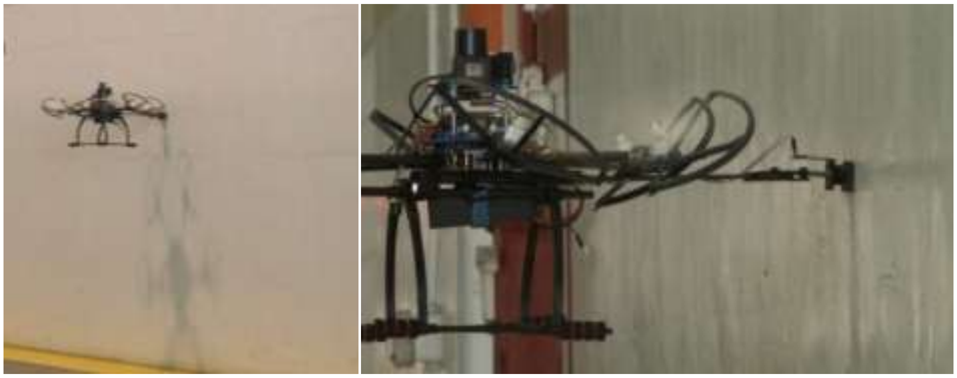

Fig. 11. Dexterous Hexrotor engaging in a Physical interaction with the vertical surface.

The autonomy on Dexterous Hexrotor is partially developed and still needs a full implementation. The tasks involving autonomous navigation, path planning and visual servoing are the parts that still needs to be implemented. The significant parts that enables the autonomy, such as the altitude hold, velocity control using optical flow sensor, physical interacting strategy using force feedback in manual mode have been successfully implemented.

## CONCLUSION

Sampling the contaminations of low-energy byproducts, performing cleanups, applying sealant are some of the tasks significant for D&D tasks. The workers performing such tasks are at a constant risk of getting exposed to radiations, risk of reaching great heights and also a lot of time involved in preparing for it. Safer and efficient robotic solution is proposed to perform the tasks and assist human workers but not replace them. This paper presents an UAV which can physically interact with the physical surfaces for sensing and sampling in the nuclear site facilities. A detailed description of Dexterous hexrotor prototype and the physical interaction strategy is provided in this paper which is required for autonomy and physical interaction. The implementation of Physical interaction strategy is presented with an experiment. The autonomy of the Dexterous Hexrotor plays an important role in releasing the burden on the operator/ worker. Nevertheless, introducing robots into the working environment enables the workers to actively participate and be safe. At the same time, the workers should be able to control the robot with very less training required. This will also improve the efficiency of accomplishing the tasks and accelerates the cleanup process.

## FUTURE WORK

We aim to build fully autonomous Dexterous Hexrotor which requires very minimal human input and no expertize in controlling them. Additionally we will develop a Swarm of Dexterous Hexrotors flying to different locations collecting samples and performing cleanups, etc. In reference to our previous work on a group of three UAVs collaborating with each other to cover larger space inside the facilities, we would like to collaborate VTOL with Dexterous Hexrotor to reach farther distances and efficiently perform any specific tasks.

As the complexity of the tasks increases, the more involvement of the human is required from a task expertise level but not from robot expertise level. Yet our main priority is to involve humans from a safe location.

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