

AERIAL MANIPULATION FOR REMOTE ROBOTIC MACHINERY DIAGNOSTICS

MG Lipsett, Rijesh Augustine and Mark Sherstan
Department of Mechanical Engineering
University of Alberta
Edmonton, Alberta T6G 2G8
Canada
+1-780-492-9494
mlipsett@ualberta.ca

Abstract: There is a growing trend of using unmanned aerial vehicles (UAVs, or drones) for inspection of industrial facilities and infrastructure. The types of inspections currently done entail remote sensing using cameras: qualitative assessment and photogrammetry using standard cameras, as well as temperature monitoring using thermal imaging cameras. The benefits of using drones are to reduce risk to inspection personnel near operating equipment, reduced cost, and improved auditability of archived data. Machine condition monitoring can benefit from this enabling technology provided that vibration monitoring and lubricant analysis can also be done remotely. Laser vibrometers can be used for remote monitoring of equipment that does not have permanently mounted, dedicated vibration monitoring sensors; but this sensing method is capital intensive, requires a laser head and controller with a typical mass of over 5 kg, and must be pointed from an appropriate direction, which may not be accessible. Lubricant analysis requires access to a lubricant sampling port and a means for collecting and analyzing the sample. A system is described for deploying a drone with a manipulator that engages the equipment of interest for vibration data collection and employs a more versatile payload for drop-tube vacuum sampling of lubricant by inserting a tube through a fill port or dip stick port and withdrawing an oil sample from the sump cavity. The key technical challenges are collision-free navigation and hovering, followed by control of dynamic deployment of the payload that connects to the machinery. A proof-of-concept system is described with very preliminary experimental results.

Key words: Aerial manipulation; automated sampling; contact inspection; inspection; lubricant sampling; remote diagnostics; robotics; unmanned aerial vehicle

1. INTRODUCTION

The main diagnostic approaches for detecting impending machinery failure are vibration spectral features, elevated temperature trends, and anomalous components of lubricant analysis [1]. Vibration and temperature measurements are readily collected by dedicated condition monitoring systems; but for lubricant sample collection and for locations where equipment is not connected to a centralized monitoring system, manual inspection remains the norm. Worker safety is a significant issue. In 2017, approximately 50 000 Canadian workers were injured due to a fall, with 27% of the fall incidents occurring at heights [3]. Remote technologies and automation can alleviate other risks to workers, reduce inspection time, and mitigate the opportunity cost of lost production by eliminating the need to stop, safe-out process equipment, and establish safe access to inspection locations.

Access to equipment can be problematic. Wheeled and tracked robots have been used for some types of inspections, but only for extremely hazardous environments such as nuclear plant inspections and security work. Low mass thermal cameras are now easily deployed by drones, and are useful for diagnostics when excess heat generation produces persistent changes in surface temperature [4]. Prior work by our research has considered the system requirements for unmanned aerial vehicles (UAVs) to be used to collect vibration data by deploying a vibration sensor to contact a target location [5]; but the issues of target location and stable deployment of a sensor remained to be demonstrated.

Having the ability to make remote condition assessments by autonomously taking a lubrication sample has the potential benefit of quickly identifying minor lubrication-related problems, which improves the chance that the issue can be addressed before functional failure occurs [2]. Being able to set an autonomous schedule to retrieve oil samples as well as vibration and temperature would establish a baseline of performance that can lead to increased reliability of machinery. If a multirotor UAV is able to retrieve samples from heights so that a worker does not need to put themselves at risk, then the UAV is an excellent source of risk mitigation as well as cost reduction, freeing inspectors for more value-added activities.

The aerial manipulation task for lubricant sampling is much more challenging than simply pressing a sensor against a target location. Taking an autonomous lubrication sample is a repetitive task consisting of flying to a predefined setpoint, removing a cap, extracting a sample, replacing the cap, and flying back to a home location with the sample for lab analysis. Although the task is repetitive at a high level, there are many external disturbances and variations that can occur between trials. These include: environmental conditions, varying cap sizes, and the accessibility to a region of interest without collisions. Creating a robust package of hardware and software can reduce disturbances, the time to complete a task, and increase the reliability of the system, in turn reducing the downtime of the UAV.

Although there are many different ways to extract lubricant samples from machinery, a sump cavity secured by a cap was selected as the primary scenario opposed to pre-installed sampling ports. This scenario is of more general interest, as providing a torque

with a UAV is a challenging control problem that is applicable to other use cases, such as opening doors to access locations, twisting process control knobs and actuating the handwheel of a process valve.

One of the most significant challenges is to compensate for reaction dynamics. When a UAV has coupled itself with the surrounding environment, the forces the UAV experiences interfere with the aerodynamics (and associated control scheme) of free flight, creating the risk of the UAV going unstable and crashing or failing its assigned task. “An analogy is to imagine a scuba diver turning an underwater valve. The diver contorts his body and aggressively kicks his legs in order to throw his body weight into turning the valve with his arms. Likewise, a UAV must ‘swim’ through air and may have to vector its body in order for the arms to dexterously manipulate an object with its arms” [6].

This paper will review relevant literature of aerial manipulation for autonomous diagnostics, describe potential components and systems to be used, provide an update on progress for a demonstration system, provide provisional conclusions, and an outline of future work.

2. LITERATURE REVIEW

Having the ability to autonomously sample and gather data is being increasingly utilized by engineers and scientists due to the efficiency and precision of the advancement of robotics [7]. Many UAVs are used for visual inspections for hard to reach or dangerous areas such as under bridges [8], various railway infrastructure [9], and high voltage power lines [10]. These use cases take advantage of both manual and autonomous flights, however they do not physical interact with the area of interest beyond imaging. Visual inspections, surveillance, monitoring and other passive tasks are now just a subset of what UAVs are capable of; and aerial robots have evolved to perform active tasks such as manipulation and physical interaction [11]. Examples include Amazon drones demonstrating the delivery of customer packages in 30 minutes or less using a hexacopter [12], two UAVs or a UAV and a ground manipulator working together to overcome payload restrictions and navigate physical barriers [13], [14], and multimodal aerial locomotion for active tool handling such as contact pipe inspections [15]. The AEROARMS Project aims to develop aerial robots with advanced manipulation capabilities for various inspections and maintenance [14]; and the reported system is highly pertinent to the challenge of interacting with machinery for diagnostics. Having various hardware and control packages such as dual arm manipulators and contact inspection platforms [16], the basic necessary components of extracting lubricant samples can be related.

One of the largest challenges with aerial manipulation is the control schemes of the UAV due to interactions with its environment [11]. UAVs interacting with the environment can be simplified into three main categories [18]: 1) Momentary coupling, interacting with objects of finite mass in the air that are not fixed to the surrounding environment; 2) Loose coupling, interacting with objects attached to the environment without securing to the environment, in tasks such as assembling, inserting, pushing, or pulling; and 3)

Strong coupling, securing or perching onto fixed objects in the environment and becoming part of it. To mitigate an unstable control system and increase the robustness due to assumptions during the modelling process, various control schemes and techniques have been proven successful such as adaptive controllers [19], adaptive sliding mode controllers [20], auto disturbance rejection (ADRC) controllers [21], gain scheduling [15] and classical proportional-integral-derivative (PID) controllers [18].

For the proposed task of autonomously extracting a lubrication sample while executing all three dynamic coupling types, there has been no detailed study found in the literature. A gas powered, ducted fan UAV design for condition monitoring of wind turbines was presented at the 32nd International Maintenance Conference in 2017 with limited details [22]. There is potential overlap within the field of aerial manipulation due to the nature of manipulators and end effectors and their multifunctional uses [16], [18]; however, the current sampling and inspection use case presented is still unique.

3. GENERAL SYSTEM DESCRIPTION

The system comprises a multirotor drone platform, a payload that interacts with fixed equipment (*i.e.*, gearbox) with an integrated sampler, and a simple manipulator to extend the payload away from the drone to engage with the equipment. All systems are electrically actuated.

Hardware

A 500 mm wheel-based MWC X-Mode Alien quadcopter frame provides a foundation for all necessary components. Four Emax XA2212 980KV brushless motors with 10 inch x 4.5 inch propellers provide a maximum of 8.6 N of thrust per motor. The motors are powered by a 3 cell LiPo battery and are controlled with Racerstar RS20A V2 20A electronic speed controllers (ESCs). One power distribution board (PDB) provides access for all electrical components and regulates voltage to the Pixhawk flight controller, Odroid C2 computer, Arduino microcontroller, and other actuation or sensing devices.

Flight Controller

To handle the control of the quadcopter a Pixhawk flight controller is utilized and comprises an inertial measurement unit (IMU), barometer, and magnetometer. The Pixhawk has a variety of interfacing ports which allows for additional components such as a global positioning system (GPS), secondary magnetometer, remote control (RC) receiver, SiK telemetry radio, and the ESC for each of the four motors. The Pixhawk runs PX4 software which is open source and allows for easy customization and deployment of new control schemes. An Odroid C2 companion computer communicates with the Pixhawk through a serial connection and handles computationally intensive tasks such as image processing. An Arduino Uno communicates with the Odroid C2 also using a serial connection for task specific applications such as analog sensing.

Coordinates and Assumptions

The axes convention to be used for describing the location and orientation of the quadcopter is North, East, Down (NED) where the right-hand rule is followed and roll ϕ occurs about the North axis, pitch about the East axis θ , and yaw ψ about the down axis. The convention can be observed in Figure 1.

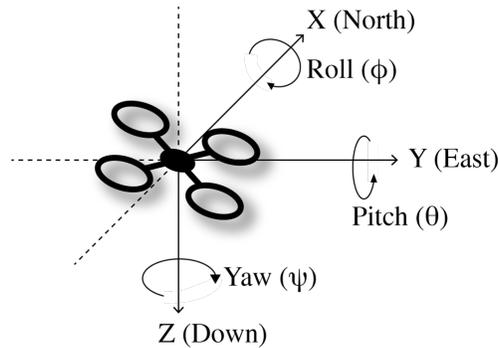


Figure 1: North East Down (NED) Reference Coordinate System

To limit the complexity of the initial modelling the following assumptions are made: 1) The quadcopter is a rigid symmetric body. 2) Thrust and drag forces produced from the propellers do not interfere with each other. 3) The ground effect is neglected.

4. POSITIONING THE QUADCOPTER

The quadcopter needs to be in a precise and stable position to be able to interface with a lubricant sampling port. Depending on environmental and situational conditions, this may be difficult for a remote human operator to achieve. If the quadcopter is outside of visual line of sight or the sampling port is too far away from the human operator, then a camera system or other relative location measurement system will be required to relay information back to the operator. Factors that affect how well a human may be able to position a quadcopter include the individual's depth perception, the individual's reaction time, camera latency, and control system latency. A GPS system may be an alternative to a human operator, but even then a traditional GPS unit will provide only sub-meter accuracy in the best-case scenario. A more expensive Real-time kinematic (RTK) GPS can yield sub-centimeter accuracy, but this approach requires ground station infrastructure and absolute surveying of equipment locations. The ideal scenario for positioning the UAV requires as little external infrastructure as possible. This is where a combination of GPS and visual servoing can lead to an inexpensive and reliable solution. In this scenario, the UAV moves into a collision-free position near the sampling port using GPS, and then utilizes visual servoing of a marker to tightly control the position of the UAV and any payload deployment.

The use of a marker is suggested where it can be placed anywhere in the environment, such that the UAV has an unobstructed view of it throughout the oil sampling procedure. A global shutter camera, attached to the Odroid C2 companion computer, continuously acquires images. Each image is processed by the computer in a multistep process,

utilizing the ArUco library [23], [24]. The ArUco library is responsible for detecting, verifying and calculating the pose of the markers. There are many marker libraries available; but ArUco was selected because it was open source and already integrated with OpenCV. The actual steps in marker detection involve thresholding the image, finding contours in the image, analyzing the contours to see which one contain a marker ID, and then finally calculating the pose of the marker relative to the camera. Figure 2, shows an ArUco marker that is coded with a 6x6 array of bits and has a marker ID of 19.

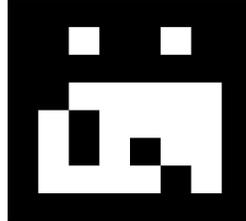


Figure 2: ArUco Marker ID 19

The accuracy of the marker pose is dependent on the number of pixels that the marker takes up. The greater the number of pixels that the marker takes up, the greater the positional accuracy. Increasing accuracy is done by either increasing the camera resolution or by increasing the size of the marker. Increasing camera resolution comes at the cost of increased processing times, whilst increasing the size of the marker makes it more difficult to install the marker and keep it in frame throughout flight manoeuvres. A trade-off is made here depending on the specific requirements of a sampling site.

After the pose of the marker is calculated, this pose is then translated from the marker coordinate frame to the quadcopter frame. The computer is preprogrammed with information of the relative location of the sampling port with respect to the marker frame of reference. This information along with the pose of the UAV is enough for the computer to calculate a trajectory. The trajectory is then sent to the PX4-based flight controller via the serial link. The quadcopter is then able to position itself to carry out the required task.

5. LUBRICANT CAP REMOVAL AND REPLACEMENT

The first complication of extracting a lubricant sample is the removal of the cap sealing the lubricant in its reservoir. Initial assumptions assume that the cap diameter ranges between 25 mm and 100 mm and uses a right hand thread. The largest force associated with removing the cap is overcoming the static friction posed by the threads. Once the static friction has been overcome, kinetic friction is experienced only on the threads and the torque requirement is much reduced. During the opposite process of reapplying the cap to the reservoir, the forces begin with kinetic friction and an inertial element reducing the required torque, and so cap removal is the constraining scenario requiring the most force. The greatest force application challenge is thus generating sufficient torque with adequate control. It is assumed that the UAV is able to securely attach itself to the cap with a gripper or customized spanner on a manipulator end effector.

Quadcopter Achieving Torque with Yaw

A potential approach for applying torque to the cap is to use the yaw produced from the quadcopter as the torquing force. Quadcopters achieve lift by spinning the propellers to generate thrust, with the direction of rotation of a propeller always opposite to its neighbour to produce opposing torques as displayed in Figure 3. To achieve yaw motion, two non-adjacent propellers must spin faster than the other pair of non-adjacent propeller pairs, creating a net aerodynamic torque that yields rotation of the quadcopter.

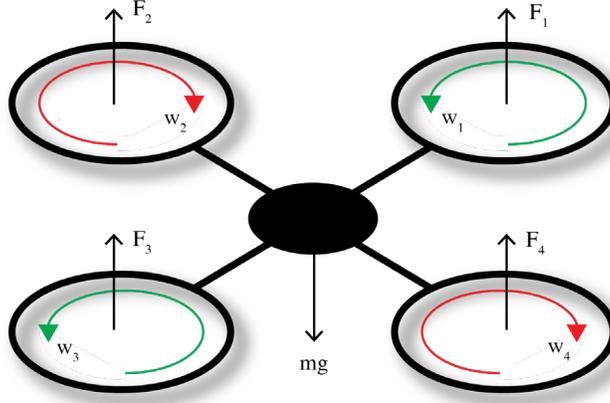


Figure 3: Free Body Diagram of Quadcopter While Hovering

In Figure 3 F_i is the thrust force produced by motor i , w_i is the angular velocity and direction of motor i , m is the mass of the quadcopter, and g is gravity. Assuming that the quadcopter is securely coupled with the cap, the following conditions must be met to generate a torque while also maintaining flight:

$$+\uparrow \sum_i^4 F_i \geq mg \quad (1)$$

$$F_1 = F_3 \quad (2)$$

$$F_2 = F_4 \quad (3)$$

$$F_1 + F_3 \geq F_2 + F_4 \quad (4)$$

$$F_1 + F_3 \leq F_2 + F_4 \quad (5)$$

To maintain level flight and controlled yaw, the UAV must produce sufficient thrust Equation (1) and the opposite pair of rotors must be producing the same amount of thrust Equation (2) and Equation (3). Referencing Figure 3, yawing clockwise tightens the cap and is achieved by the conditions in Equation (4), while unscrewing a cap is achieved by rotating counter clockwise as constrained by Equation (5). Based on the quadcopters thrust to lift ratio the torque limitation can be observed as the UAV must keep itself airborne and can only utilize half of its motors and a percentage of its thrust to achieve yaw. This was experimentally viewed in [25] where a quadcopter UAV was tasked with a strong coupling task of opening a valve. Although the valve had reduced friction and was for demonstration purposes, the UAV struggled to produce the necessary torque. It should be noted that a classical controller using a PID loop was used [23], which is promising for ease of implementation and providing a foundation to which more complex control schemes might be used with improved results.

Quadcopter Achieving Torque through Rotation of its Thrust Vector

With the limited torque available by utilizing only the yaw of the quadcopter, a rotated thrust vector is a more likely way to deliver sufficient torque to open the cap. There are two variations to produce this thrust vector.

The first alternative uses a moment arm from an extended arm. Once the quadcopter is secured to the cap with an elongated end effector, the UAV rolls about the connection point at its center of mass, transitioning the thrust vector from the upwards direction into vertical and horizontal components with an angle ϕ . Figure 4 displays the forces due to the roll angle ϕ .

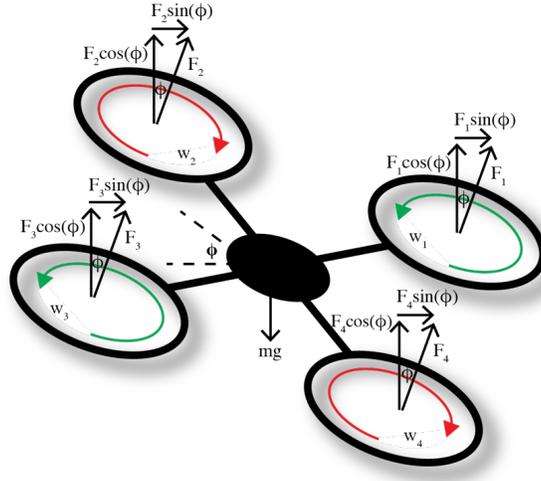


Figure 4: Free Body Diagram of Quadcopter Executing Clockwise Rolling Motion

Referring to Figure 4 and using the same variable definition as defined previously, the following conditions are required to keep a constant tangential force and the UAV airborne:

$$+\uparrow \sum_i^4 F_i \cos(\phi) \geq mg \quad (6)$$

$$F_1 = F_4 \quad (7)$$

$$F_2 = F_3 \quad (8)$$

$$F_1 + F_4 \leq F_2 + F_3 \quad (9)$$

$$F_1 + F_4 \geq F_2 + F_3 \quad (10)$$

Summing the horizontal components of the thrust vector yields a force P as defined in Equation (11). As the quadcopter is assumed to be symmetric, varying the distance r from the center of the quadcopter to the cap will increase the torquing force as observed in Equation (12) where clockwise rotation would occur with conditions from Equation (9) and counter clockwise rotation would occur with conditions from Equation (10).

$$P = \rightarrow \sum_i^4 F_i \sin(\phi) \quad (11)$$

$$\tau = r \times P \quad (12)$$

Maximizing ϕ produces the largest amount of horizontal thrust as long as the UAV produces enough vertical lift to remain airborne. Alternatively the moment arm r can be extended to produce a greater torque as outlined in Equation (12) and in turn the reduce the roll angle whilst providing the same amount of torque. In reality, the moment arm must be kept at a reasonable length for maneuverability of the UAV and keeping a balanced center of mass. One major aspect of this approach is the rolling motion for a quadcopter is a common and simple task to execute and control. An example relating to the proposed method can be found in [26] where a three degree-of-freedom helicopter rotating about a center point is developed for testing various control schemes. The first approach only works in a region that allows collision-free motion of the drone.

The second method for rotating the thrust vector to generate a torque for cap removal is to rotate all the rotors with respect to the frame of the UAV. Such a design turns an under-actuated quadcopter into an over-actuated machine. To model such a system six coordinate frames must be used as depicted in Figure 5. Frames one through four correspond to the respective motors and their orientation, frame B corresponds to the body frame of the UAV about its center of mass, and frame G corresponds to a ground reference frame.

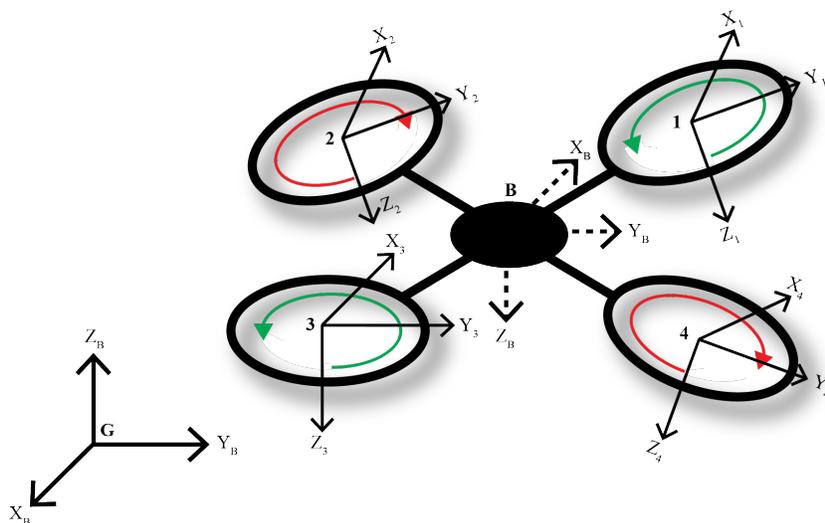


Figure 5: Rotor, Body & Ground Coordinate References for Rotating Rotor Quadcopter

The modelling of the dynamics is a non-trivial problem consisting of rotational matrices based on many different frames and coordinates. Such derivations have been achieved in both [27] and [28] where physical and numerical experiments were respectively conducted with success. Similar to the first proposed concept of thrust vector rotation, the ability to vary the rotor angle allows for the harnessing of multiple rotors thrust as long as enough lift is generated to stay airborne. Having the ability for each rotor to move independent of the others allows for an extremely maneuverable vehicle with the capability to produce high amounts of torque in a relatively small footprint. With this proposed method a UAV can achieve torque from above the cap without the need of a torquing arm. The benefits come at a cost of an increased complexity of mechanical design (and controller design); however, the methodology and ideology has been proven successful in other applications [29].

Quadcopter Achieving Torque by Coupling Itself to the Environment

To reduce the complexity of producing a torquing force with a UAV, the UAV can be coupled to the surrounding environment. Affixing the quadcopter can be achieved in a variety of different ways, such as adhering itself to the ground (*i.e.*, a steel gearbox structure) with electromagnets. Alternatively the UAV can stay airborne by securing itself to the throat of the lubricant cap with a gripper and having a secondary device provide torque to the cap from the new fixed reference. Both proposed methods and any such derivatives greatly simplify the torque limitation issue described above, as well as the problem of collision-free trajectories near equipment. The simplification comes as the UAV is stationary after approaching and landing on the structure and a secondary mechanism delivers the torque to remove the cap, as opposed to the UAV directly being part of the torquing mechanism. Such a mechanism makes many assumptions of the surrounding environment and potentially limits the autonomous capabilities of focusing on a single cap as a target; but this strategy likely increases the robustness and repeatability of the actuation task.

6. LUBRICANT SAMPLING

Once the cap has been successfully unthreaded it must be positioned so that the lubricant reservoir is accessible. Using the assumption that the cap is gripped sufficiently tightly, once freed the cap can be moved away from the access port by the end effector or by the UAV performing a slight hover to create a gap in the Z direction. With the reservoir exposed, the task becomes a pin-in-hole or loose-coupling scenario in which a sampling tube is inserted and lubricant is extracted. Based on industry standards, approximately 80 mL of lubricant is sufficient to perform the analyses necessary for machinery diagnostics [30-32]. To avoid cross contamination between samples, only one sample is taken per flight so that the sampling unit can be cleaned or swapped before the next mission (although a magazine could be employed on a larger UAV to collect multiple samples). To get a lubricant that truly reflects the state of the machinery of interest, the sample should be taken from the middle region of the sump to avoid the sludge line [33] and particle fallout [34]. Four possible designs are proposed for the drop tube sample extraction: a peristaltic pump with tubing, a vacuum pump with tubing, an evacuated bottle and tube, and a container sample lowered directly into the reservoir.

Peristaltic Pump

A peristaltic pump using positive displacement is suggested to limit contamination. Only the tubing requires cleaning or replacement between sampling missions opposed to the entire pump assembly. The cyclic motion of the peristaltic pump allows for an approximation of a fixed amount of fluid for each rotation reducing the need for fluid level sensors or other monitoring techniques. Additionally the pump can handle a range of viscosities and prevents backflow. The largest drawback from using a peristaltic pump is the pump is constantly under load increasing power consumption. Due to the UAV being a battery-operated system with a finite amount of power operating the pump for

prolonged periods of time or adding a secondary power source greatly reduces the total possible mission or flight time.

Vampire Pump

A common industry solution for drop tube sampling is termed “vampire pump” [31] which is based on a piston suction pump design. A piston is actuated in a reciprocating linear motion creating a partial vacuum, which draws fluid into a sampling container. If done properly the risk of contamination is minimal, however should too much fluid be sampled the lubricant can flow into the plunger cavity creating the risk of cross contamination and requirement for cleaning. Due to the linear actuation of the pump, quantifying the fluid volumes can be easily approximated and a mechanical advantage in the form of a rack and pinion can reduce the power consumption of the system. Due to the linear nature of the pump, a large relative foot print with respect to the UAV may be required. Optimizing spatial constraints, center of mass, and total weight may pose a problem with such a design.

Evacuated Bottle

Using an evacuated bottle would eliminate the requirement for any pumping or significant actuation. Commercial products are available such as the Simplo sample bottle [35] where once a sample tube is submerged a valve on the lid is rotated (*i.e.*, by a servo) and the pressure difference draws the lubricant sample into the bottle. Although an evacuated bottle can only be used as long as its internal pressure remains below atmospheric it can handle a range of high and low viscosities. The primary difference in sampling time depends on the viscosity of the liquid with high viscosities being fast and low viscosities slow. Due to the vacuum and the sample retrieval time being a function of some unknown viscosity a fluid level indicator will have to sense when the valve should be closed again once the required quantity of fluid is acquired. With the small footprint of an evacuated bottle this is of little concern.

Container Sampling

A cup sampler method is proposed for extracting the required lubrication sample by lowering a cup or bottle into the lubricant sump. The lid separates from the sampling container to allow the lubricant to flow into the container. Once a predetermined time threshold is met the lid is replaced and the container is retrieved from the sump. The proposed method is extremely simple and robust, however comes with challenges. The outer diameter of the sampling container must not be larger than the inner diameter of the reservoir entrance. Lowering the container into the optimal sample region provides a challenge and may require rigid actuation. Upon removal of the sample, the entire container will be covered with the lubricant and must be cleaned or contained before flight to reduce spilling and contamination of the surrounding environment.

7. VIBRATION MONITORING AND TRAJECTORY

The hardware required for taking a vibration measurement is fairly straightforward when compared to oil sampling. An arm has been developed with an electromagnet and a vibration sensor at the end. Dampening foam is used to isolate the vibration gathering equipment from vibrations generated by the quadcopter. To ensure the center of gravity of the UAV is maintained, a counterweight is used at the other end of the arm. The vibration sensor at the end of the arm uses a ± 2 g MEMS accelerometer. A Fourier transform is applied to raw accelerometer measurements to represent the vibrations in the frequency domain. Once in the frequency domain, the relative and absolute strength of vibrations across the frequency spectrum can be analyzed to detect faults.

The trajectory generation is done by scheduling setpoints. Before the UAV reaches a setpoint, a new setpoint is sent. When this scheduling is done at a high enough frequency, linear 2D motion is no longer perceived as a series of line segments, but as a smooth curve. Figure 6 shows the simulated position of the quadcopter vs the position of the setpoint. Arrows indicate the path the UAV would take if a new setpoint is not sent. This method in conjunction with the PID position controller on the autopilot, allows for a smooth trajectory that ends in a gentle touch.

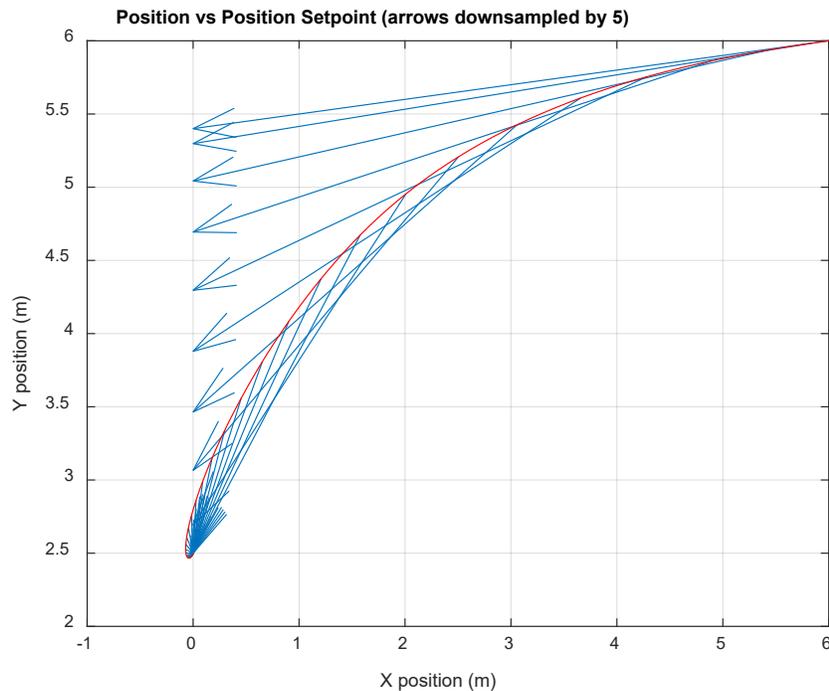


Figure 6: Position vs Position Setpoint (arrows down sampled by 5)

8. PROTOTYPE DEVELOPMENT TO DATE

Quadcopter

The quadcopter previously described is not a complete kit; however, all essential components are commercially available off-the-shelf for reliability and ease of characterization. The MWC X-Mode Alien quadcopter frame does not satisfy the symmetric rigid body assumption proposed, but it does provide an extensive structural frame that can utilize large propellers for large amounts of thrust. There is ample room to organize sensors, manipulators, controllers, and batteries. The UAV with its essential elements and companion computer is displayed in Figure 7. The Pixhawk flight controller stores all flight data (such as attitude, position, and motor output) to an onboard SD card as well as wirelessly transmitting real-time data to an off-board computer using a 915 MHz SiK telemetry radio.



Figure 7: Top View of Quadcopter with Key Components and Companion Computer

Adaptive Gripper

An adaptive gripper end effector was designed based on the Robotiq 2F-140 [36] due to the wide range of tasks the gripper can perform. The gripper was 3D printed using polylactic acid (PLA) filament and assembled with standard metric hardware. An elastomeric surface was added to the inner contact surface of the gripper to increase the coefficient of friction. To actuate the device, a HS-645 MG ultra torque servo rotates two gears which are fixed to linkages. The gripper is controlled by a switch on an RC transmitter that passes a signal to the receiver onboard the UAV and then through the Pixhawk flight controller auxiliary pins. The auxiliary pins can easily be adapted into an autonomous control scheme, which allows flexibility for future development. Using camera-mounting holes located on the front of the UAV, the gripper was installed and counterbalanced with a LiPo battery to balance the UAV center of mass and minimize the effect on the controller. An image of the gripper fixed to the UAV is shown in Figure 8.



Figure 8: Adaptive Gripper Prototype Mounted on UAV

The first iteration of the gripper design was able to span from 0 mm when fully closed to 200 mm when fully open. The gripper can grasp a rigid, smooth plastic container weighing over 1 kg and successfully move it even when the payload was subjected to acceleration forces.

Flight trails were conducted to observe the effect actuating the gripper would have on an unmodified PX4 control scheme. The main concern was actuating the gripper changes the UAV center of mass and creates an inertial disturbance. Results from one flight trail are displayed in Figure 9.

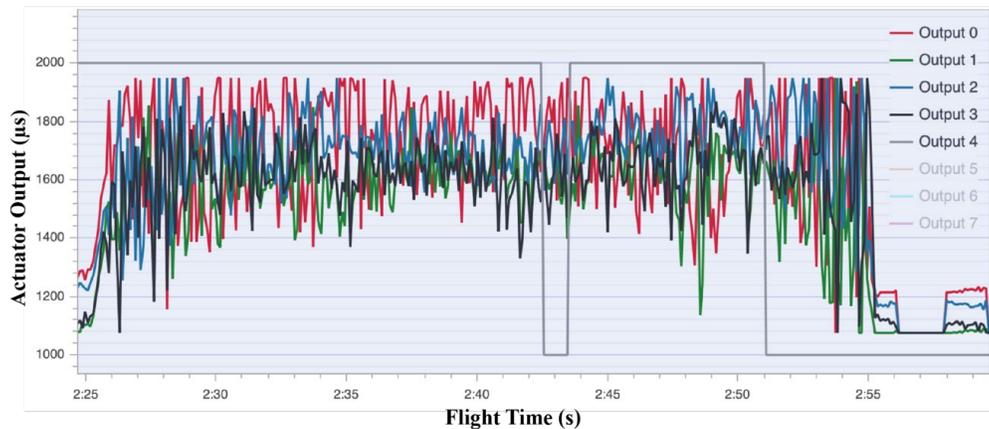


Figure 9: Main Actuator Outputs in Stabilized Flight Mode

Outputs 0 through 3 correspond to signals being sent to each of the motors in stabilized flight mode, and output 4, the grey line, is the signal that is actuating the gripper. The gripper was actuated three times: at 2:43, 2:44 and 2:51. During these three points in time, it can be observed that it had little to no effect on the flight performance, which is a promising result for the testing platform and use of the gripper for aerial manipulation.

Linear Clamp Gripper

The linear clamp gripper was constructed with the same manufacturing techniques and hardware as the adaptive gripper. The design was selected as an alternative to the adaptive gripper as this effector would allow approaching a cap from above opposed to perpendicular of the axis of rotation. This method will allow for testing the torque output produced by the yaw of the quadcopter and also provide a concept for future design considerations. A shaft is driven by a worm drive that is fixed to a continuous rotation HS-645 MG ultra torque servo attached to a gear train that outputs translational motion through a rack and pinion. Two sets of clamps are fixed to opposite racks that move in opposing directions, delivering a clamping range between 25 mm and 100 mm. To control the range of motion of the jaws, limit switches provide a physical to digital reference point. The current prototyped configuration is shown in the photographs in Figure 10.

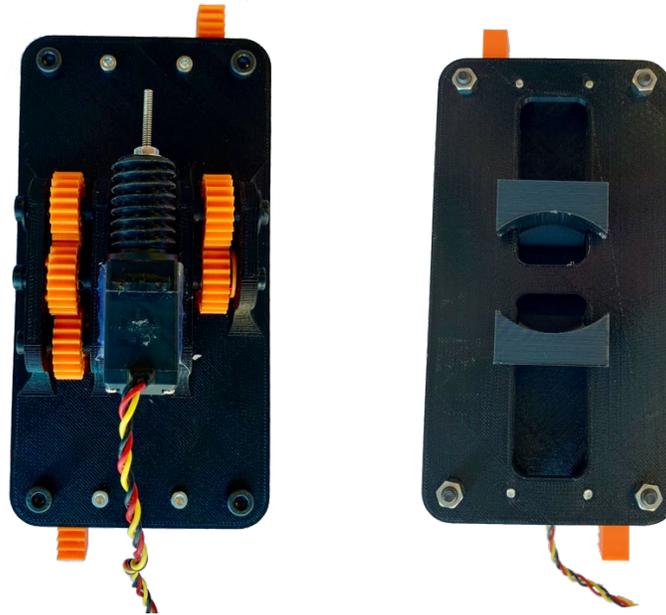


Figure 10: Linear Clamp Gripper Prototype (Top View Left, Bottom View Right)

Initial test results of the linear clamp gripper proved successful in multiple trials where the prototype successfully twisted off a moderately torqued 75 mm diameter cap with the aid of a planetary carrier rotating device. Although not quantified, the gripping force was greater than the adaptive gripper (at the cost of actuation time). As the required torque of the cap was increased, the limiting factor was the friction between the jaws and the cap. Similar to the adaptive gripper, a high friction surface was used; however, further design and experimentation will be required to characterize the response.

9. CONCLUSIONS AND FUTURE WORK

In this paper the framework for an autonomous lubricant sampler is explored. The primary challenge is executing a torque to remove the lubricant cap so a sample can be extracted from the reservoir. Four solutions were proposed where torque is to be achieved

using the UAV's yaw, rotating the thrust vector with a rotation joint and moment arm or with over actuated rotational rotors, and by coupling the UAV to its environment. Lubricant extraction can be achieved by using positive displacement pumps such as peristaltic or vane pumps, an evacuated bottle, or a container sampling approach. Vibration data acquisition and UAV trajectories were presented and initial prototyping and test results for the UAV and two end manipulators were then discussed.

The next testing stage is to use the actuator to couple the UAV with the environment and observe the effects. Once results and any required changes have been implemented the UAV will be used to rotate a cap with a resistant torque. Upon completion of cap removal the fluid extraction portion of the design will be more thoroughly considered.

In terms of the gripper modifications, lock nuts must be used to deal with the movement of the linkages and vibrations from the UAV. The range of actuation, geometry, and required gripping strength will need to be fully quantified and the gripper will be resized accordingly. The linear clamp gripper has yet to be tested on the UAV, but it is designed with mounting points to balance the center of mass of the UAV. Further future design considerations include reducing the size of the apparatus and decreasing the actuation time while maintaining a similar clamping force. Similar to the adaptive gripper, the forces to be experienced should be better quantified to aid the design and construction of the device and reduce size and mass. A full range of trials remains to be done for both manipulators, including detailed in air actuation, environmental coupling, and cap torquing.

The remaining future work can be summarized as quantifying a range of cap torque requirements, selecting a torquing and sampling method, developing a system and control package for cap removal and sampling, and performing experimental validation.

Acknowledgments

Dr. Duncan Elliott provided key insights into the visual navigation technique. Nicolas Olmedo provided technical and experimental support. Funding from the Natural Sciences and Engineering Research Council is gratefully acknowledged.

References

- [1] M. M. Botha, "Electrical machine failures, causes and cures," 1997 Eighth International Conference on Electrical Machines and Drives (Conf. Publ. No. 444), Cambridge, UK, 1997, pp. 114-117.
- [2] "Fluid Life Oil Analysis", *Fluidlife.com*, 2018. [Online]. Available: <https://www.fluidlife.com/services/condition-monitoring/fluid-analysis/oil-analysis/>. [Accessed: 02- Dec- 2018].
- [3] The Association of Workers' Compensation Boards of Canada (AWCBC) (2017). *National Work Injury, Disease and Fatality Statistics (NWISP)*. 2015-2017. [online] The Association of Workers' Compensation Boards of Canada (AWCBC). Available at: http://awcbc.org/?page_id=89 [Accessed 11 Feb. 2019].
- [4] M.G. Lipsett, R. Vaghar Anzabi (2013). "Seasonal effects on haul truck tyre life."

Int'l J Strategic Eng Asset Mgmt, Vol1, No3, pp 316 - 327

[5] M.G. Lipsett, N. Olmedo, B. Tesfay (2017). "A Wireless System for Conducting Remote Vibration Monitoring Using a Remotely Operated Deployment Robot." *Condition Monitor* 365, Inst British Non Dest Testing, August, pp 6-9.

[6] T. Ricci, "Unmanned Aerial Vehicles Soar High", *Asme.org*, 2012. [Online]. Available: <https://www.asme.org/engineering-topics/articles/robotics/unmanned-aerial-vehicles-soar-high>. [Accessed: 22- Jan- 2019].

[7] M. Dunbabin & L. Marques (2012). Robots for environmental monitoring: Significant advancements and applications. *IEEE Robotics & Automation Magazine*, 19(1), 24-39.

[8] H. Yu, W. Yang, H. Zhang and W. He, "A UAV-based crack inspection system for concrete bridge monitoring," *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Fort Worth, TX, 2017, pp. 3305-3308.

[9] K. Máthé, L. Buşoniu, L. Barabás, C. Iuga, L. Miclea and J. Braband, "Vision-based control of a quadrotor for an object inspection scenario," *2016 International Conference on Unmanned Aircraft Systems (ICUAS)*, Arlington, VA, 2016, pp. 849-857.

[10] L. F. Luque-Vega, B. Castillo-Toledo, A. Loukianov and L. E. Gonzalez-Jimenez, "Power line inspection via an unmanned aerial system based on the quadrotor helicopter," *MELECON 2014 - 2014 17th IEEE Mediterranean Electrotechnical Conference*, Beirut, 2014, pp. 393-397.

[11] F. Ruggiero, V. Lippiello & A. Ollero, "Aerial Manipulation: A Literature Review," in *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 1957-1964, July 2018.

[12] "Amazon.com: Prime Air", *Amazon.com*, 2019. <https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011> [12-Feb- 2019].

[13] H. Kim, H. Seo, C. Y. Son, H. Lee, S. Kim and H. J. Kim, "Cooperation in the Air: A Learning-Based Approach for the Efficient Motion Planning of Aerial Manipulators," in *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 76-85, Dec. 2018.

[14] N. Staub *et al.*, "The Tele-MAGMaS: An Aerial-Ground Comanipulator System," in *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 66-75, Dec. 2018.

[15] H. W. Wopereis *et al.*, "Multimodal Aerial Locomotion: An Approach to Active Tool Handling," in *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 57-65, Dec. 2018.

[16] A. Ollero *et al.*, "The AEROARMS Project: Aerial Robots with Advanced Manipulation Capabilities for Inspection and Maintenance," in *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 12-23, Dec. 2018.

[17] "Multimedia | AEROARMS", *Aeroarms-project.eu*, 2019. [Online]. Available: <https://aeroarms-project.eu/category/multimedia/>. [Accessed: 12- Feb- 2019].

[18] M. Orsag, C. Korpela, S. Bogdan and P. Oh, "Dexterous Aerial Robots—Mobile Manipulation Using Unmanned Aerial Systems," in *IEEE Transactions on Robotics*, vol. 33, no. 6, pp. 1453-1466, Dec. 2017.

[19] I. Palunko, P. Cruz and R. Fierro, "Agile Load Transportation : Safe and Efficient Load Manipulation with Aerial Robots," in *IEEE Robotics & Automation Magazine*, vol. 19, no. 3, pp. 69-79, Sept. 2012.

[20] S. Kim, S. Choi and H. J. Kim, "Aerial manipulation using a quadrotor with a two DOF robotic arm," *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Tokyo, 2013, pp. 4990-4995.

- [21] Q. Wang, H. Xiong and B. Qiu, "The Attitude Control of Transmission Line Fault Inspection UAV Based on ADRC," 2017 International Conference on Industrial Informatics - Computing Technology, Intelligent Technology, Industrial Information Integration (ICIICII), Wuhan, 2017, pp. 186-189.
- [22] M. Holloway, *The Use of Drone Technology for Remote Oil Sampling - 32nd International Maintenance Conference*. 2018. Available: <https://reliabilityweb.com/videos/article/the-use-of-drone-technology-for-remote-oil-sampling> [Accessed: 14- Feb- 2019].
- [23] "Speeded up detection of squared fiducial markers", Francisco J.Romero-Ramirez, Rafael Muñoz-Salinas, Rafael Medina-Carnicer, *Image and Vision Computing*, vol 76, pages 38-47, year 2018
- [24] "Generation of fiducial marker dictionaries using mixed integer linear programming", S. Garrido-Jurado, R. Muñoz Salinas, F.J. Madrid-Cuevas, R. Medina-Carnicer, *Pattern Recognition*:51, 481-491,2016
- [25] M. Orsag, C. Korpela, S. Bogdan and P. Oh, *TRO2015.mp4*. 2017. Available: <https://ieeexplore.ieee.org/ielx7/8860/8113882/8059875/tro-orsag-2750693-mm.zip?tp=&arnumber=8059875>
- [26] Mirko Brentari, Paolo Bosetti, Isabelle Queinnec, Luca Zaccarian. Benchmark model of Quanser's 3 DOF Helicopter. Rapport LAAS n° 18040. 2018. <hal-01711135>
- [27] M. Kamel *et al.*, "The Voliro Omniorientational Hexacopter: An Agile and Maneuverable Tiltable-Rotor Aerial Vehicle," in *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 34-44, Dec. 2018.
- [28] C. Yih, "Flight control of a tilt-rotor quadcopter via sliding mode," *2016 International Automatic Control Conference (CACSS)*, Taichung, 2016, pp. 65-70.
- [29] "VOLIRO", *Voliro.ethz.ch*, 2018. [Online]. Available: <https://www.voliro.ethz.ch>. [Accessed: 13- Feb- 2019].
- [30] "Guide to Submitting an Oil Sample | Same Day Testing & Results", *Apex Oil Lab*, 2017. [Online]. Available: <https://apexoillab.com/submitting-an-oil-sample/>. [Accessed: 17- Jul- 2018].
- [31] "SAMPLING HARDWARE 38U Series Vampire Pump", *Fluidlife.com*, 2018. [Online]. Available: https://www.fluidlife.com/wp-content/uploads/2014/11/Sampling_VampirePump.pdf. [Accessed: 16- Jul- 2018].
- [32] "COMPLETE TEST LISTS", <https://polarislabs.com/testing/oil-analysis/>, 2018. [Online]. Available: <http://www2.eoilreports.com/CompleteTestList>. [Accessed: 19- Jul- 2018].
- [33] "Oil Analysis Sampling Procedures | Fluid Life", *Fluidlife.com*, 2019. [Online]. Available:<https://www.fluidlife.com/services/condition-monitoring/fluid-analysis/sampling-resources/sampling-procedures/>. [Accessed: 24- Jul- 2018].
- [34] D. Troyer and J. Fitch, "Oil Analysis Basics - Second Edition", Noria Corporation.
- [35] "Oil Sampling Made Easy: Simple sample bottle", *Relyassistllc.com*, 2018. [Online]. Available: <http://www.relyassistllc.com/#simpleInfo>. [Accessed: 14- Feb- 2019].
- [36] "2F-85 and 2F-140 Grippers - Robotiq", *Robotiq.com*, 2018. [Online]. Available: <https://robotiq.com/products/2f85-140-adaptive-robot-gripper>. [Accessed: 01- Feb- 2019].