A Novel Approach to Autonomous Aerial Manipulation using Multiple Drones

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ABSTRACT

The International Aerial Robotics Competition (IARC) in it's 9th mission proposes the replacement of a communication module placed on a mobile platform situated nearly 3 km from the base. The IARC has introduced 3 new challenges, namely, manipulation of large objects, aerial robotic repair on a mobile platform and complete on-board computation. A multi-drone system is proposed, carrier drone will deploy another drone for module replacement and return. The drones interact with their environment through module detection, mast detection and localisation. This paper provides a detailed description of different modules and how they are integrated.

INTRODUCTION

An important feature of aerial robots is to perform all tasks with onboard computers only, which enables them to function independently in remote locations far from the base. The previous missions of IARC have demonstrated autonomous indoor flight behaviour, swarm robotics, human-drone interaction. In the ninth mission, the teams were asked to demonstrate precise robotic arm manipulation to replace a 2 kg communication module on a mobile platform. This capability can be used for the maintenance of equipment which would decrease the risk for maintenance technicians. This paper demonstrates the approach to this mission by Team AeRoVe, IIT Bombay, using a mother-daughter drone system with a gripper and replacement mechanism.

PROBLEM STATEMENT

For the IARC Mission 9, goal is to develop a fully autonomous aerial robot that will fly a distance of approximately 3 km (1.9 miles) to apprehend a Hunter-Killer vessel and perform the task of replacing the communication module payload that it is carrying. The aerial robot should fly at less than an altitude of 15 m (49 ft) and weigh less than 90 kg (198 lbs). The drone(s) must be able to perform the task of replacement and return to its launch site in under 9 minutes. The vehicle is to be self-contained (no off-board computing) and must be able to self-navigate using GPS, visual cues, or magnetic heading.

CONCEPTUAL SOLUTION

We propose a solution of multi-drone system to complete this mission in 9 minutes. The carrier drone (mother drone) will deploy the daughter drone after completing it's 4 laps around the two pylons. The daughter drone will move towards the mast and the carrier drone will start it's the return journey. The daughter drone will approach the mast by first

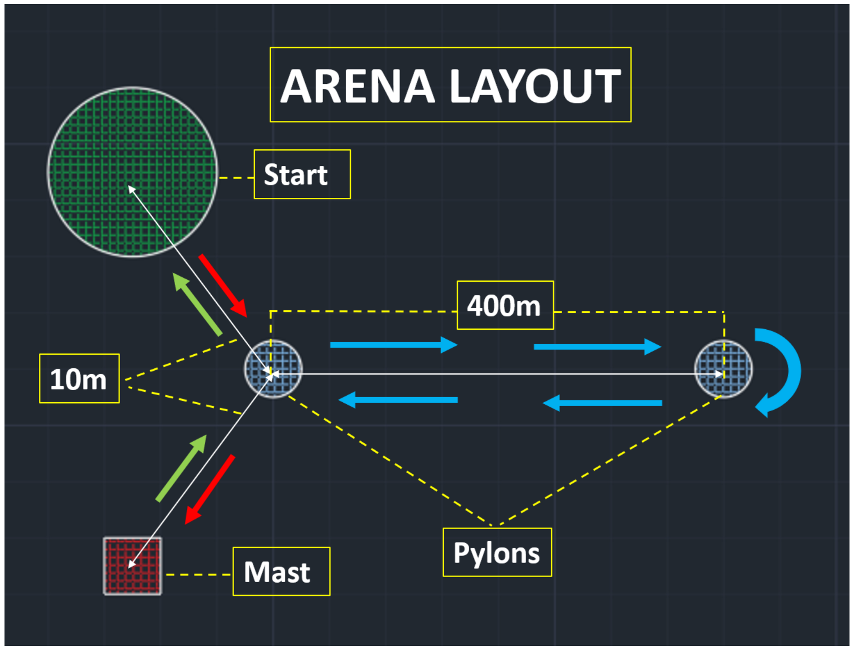


Figure 1. Layout of the arena

detecting navigation lights and then the communication module.
The problem is divided into the following sub-systems and later integrated.

- **Controls:** Overall flight control of both drones and controlling the gripper for module replacement. Providing pose values to a package for vehicle movement.
- **Mechatronics:** Manufacturing of both drones and their power system. Conceptualising and constructing the mechanical gripper for module replacement.
- **Perception:** Pose estimation of mast and navigation lights with respect to drone.
- **localisation:** Obtain the location of both drones at all times with high accuracy.

YEARLY MILESTONES

For the following year, team's main objective is to fine-tune current design of vehicle(s) to make them more energy-efficient and feasible in terms of manufacturability and flight performance. Subsequently, intensive and exhaustive testing of the hardware would be conducted throughout the year to increase the soundness of vehicle(s) and to ensure high competency of their designs. To ensure efficient and stable flight, all algorithms will be implemented and tested on the aerial vehicle(s).

AIR VEHICLE

As discussed in conceptual solution, a mother-daughter multi-drone system is used to achieve all mission goals. Let's have a closer look at the two.

Mother Drone

Considering the key goals of mothership following are certain requirements to be fulfilled

- Capability to move at high speeds while carrying the enormous weight of the payload.
- High structural loading on the mothership due to aerodynamic forces and payload.
- Sufficient power to have the required flight time to reach till the mast and return back.
- Good enough space to accommodate payload and clearances to deploy the daughter.

To address the above mentioned problems we came up with the following design

- A hexacopter configuration is used to suffice throttle requirements. It also gives 6 points to alter thrust and ensure more stability & manoeuvrability at high speeds.
- The entire frame of the mothership is made from composite truss beams. Each beam is made by connecting two planar truss structures using T beam elements. This structure helps a lot in reducing weight and provides all the required strength to the mothership.
- Keeping the base of the hexacopter as a hexagon itself leaves a good amount of space in the centre to place the daughter drone and the gripper mechanisms.
- 6 motors also give throttle to carry 4 batteries that can power the drone for 9+ mins.

Daughter Drone

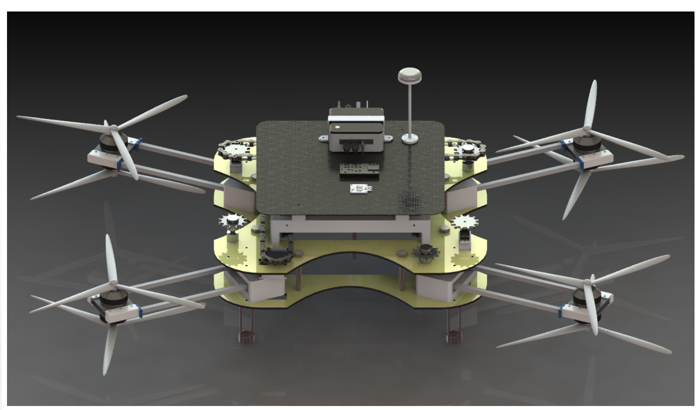
The purpose of the daughter drone is simply to hover near the mast carrying all the mechanisms and hence its design requirements are very different from that of the mothership.

- Sufficient thrusts and power to hover a 28 Kg system for nearly 4 minutes.
- Minimum weight design with high strength to hold the hanging payload
- Enough space to accommodate the mechanism for planar movement of the grippers.
- Provisions for closer reach to the mast and module during replacement maneuvers.

The above mentioned requirements were fulfilled by the following design

- An Coaxial Octocopter configuration is selected to suffice the high throttle requirements. It is further customised to form a stretched 'X' shape as seen from the top that allows it to reach close to the swaying mast without any collisions of the propellers.
- The body of the daughter drone is almost hollow, 2 carbon fibre plates are connected to hold arms. Carbon fibre reduce drone's structural weight by 60% compared to metallic alternatives while maintaining strength. $(Density : Al = 2.7\ g/cm^3$, $Cf = 1.1\ g/cm^3)$.
- It has a square opening at the centre to accommodate the planar motion mechanism.

(a) Mother Ship



(b) Daughter Drone

Figure 2. Engineering Designs

Drone specifications

TABLE 1. VARIOUS PARAMETERS CALCULATED FOR BOTH THE AIR VEHICLES

Parameter	Mother	Daughter
Service time	9 min	4 min
Structural Weight	24 Kg	16 Kg
Payload	28 Kg	8 Kg
Motors	110 KV - 16.1 Kgf	320 KV - 7.2 Kgf
Propellers	30 W x 9 P in	22 W x 6.6 P in
Required Thrust per motor	8.7 Kgf	3.5 Kgf
Battery Capacity (60% Discharge)	19.2 Ah	19.2 Ah
Battery Configuration	4 x 16 Ah (2S2P)	2 x 16 Ah (2S)

Structural Analysis

Stress analysis performed on the frame of mother-ship highlights the effectiveness of truss based structure. Even under 1.5 times of the optimal usage forces, the hub of the drone remains effectively undeformed. The maximum deflection seen in the frame is 1 micron only, compared to a deflection of 100 microns for aluminium sheets. The reason being that sheets experience bending, whereas, for truss links, it transforms to compressions and tension. This structure also provides 60% mass reduction due to its cage-like build.

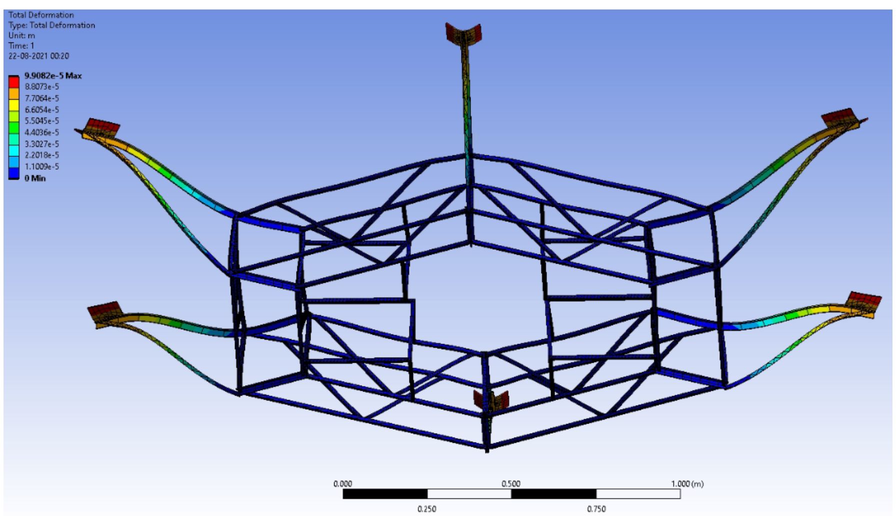
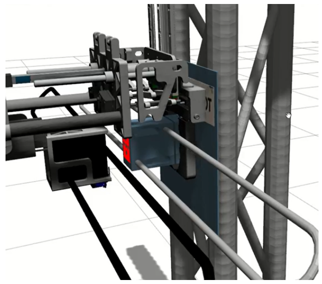


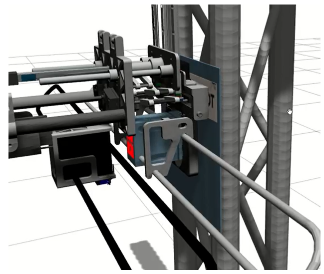
Figure 3. Mother-Ship deformation - 80Kgf thrust, standard earth gravity 30Kgf payload

Module and mast manipulation

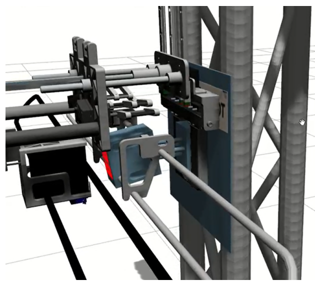
Two tasks are required to be completed once daughter drone reaches the mast. First is the removal of the already installed module and second is installation of the module carried by the daughter drone. The communication module blocks are inserted into horizontal rods coming out of the mast board and held on with a magnet. The force required to take out the module by overcoming the magnetic force is around 40 N. Moreover, the module is placed on a swaying mast thus, we need a gripper that fits tightly into some part of the module and also another gripper to fix onto the swaying mast to pull the module out. For this purpose, we have designed a replacement mechanism with both these components. Details are mentioned in the following sections.



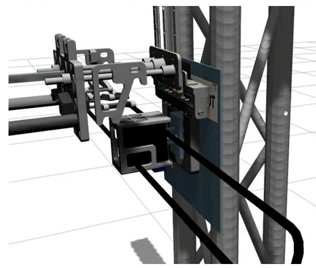
(a) Approaching



(b) Locking antennae



(c) Pulling



(d) Replacing

Figure 4. Process of module removal and replacement

Gripper design

The replacement mechanism attached to daughter drone is the most integral component of design. It consists of 2 grippers, each with 2 degrees of freedom, one for holding the mast and the other for replacing the module. The working principle of the module gripper is the same as that of a parallel arm gripper. It has grooves in which the rods of the module would fit in perfectly. It would facilitate removal of the module after being locked in position. The mast gripper keeps gripper mechanism stationary with respect to the module and mast. It simply grapples the small extrusion on the mast board, having face dimensions the same as the module.

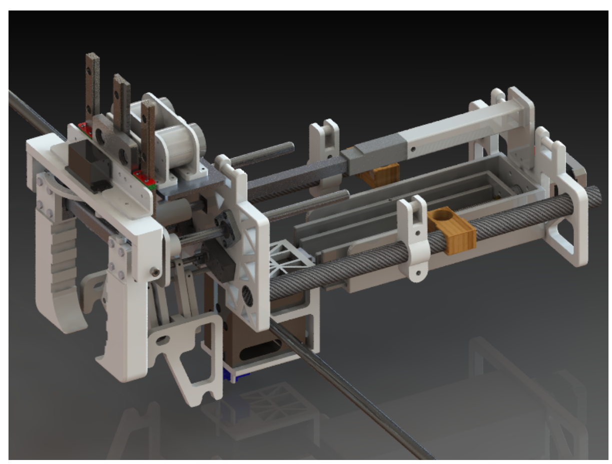


Figure 5. Gripper & Replacement Mechanisms

Gripper mechanism and functioning

The mechanism will accomplish the task of communication module replacement by employing a series of clever manoeuvres:

- The first step comprises of lowering the gripper and grabbing the swaying mast, thus ceasing any relative motion between the gripping mechanism and the mast.
- Next, the module is extracted from the mast by employing a specially designed gripper that slides onto the module antenna and pulls it out using a linear actuator.

- The linear actuator pushes the mast away from the gripper system, which indirectly pulls out the communication module.
- As soon as the communication module comes out, it would fall on the ground as it doesn't have support from bottom, saving the system from carrying 2kg extra load.
- Finally, the new module can be slid into place, completing the process of replacement.

The replacement mechanism is made with lightweight material to keep the mass to a minimum, thus reducing the daughter drone load.

Flight Control stack

A Linux-based system running on a Jetson Xavier NX onboard computer is used. The Robot Operating System (ROS) [9] framework was used for communication between different flight modules. The flight control stack integrates ROS packages of Localisation, Controls and AI submodules into a cohesive system.

Architecture

The conceptual model of the system architecture is illustrated in Figure 6. It consists of various sensors, actuators, flight controller, onboard computer, and software modules by different subsystems that will work together to implement the overall system.

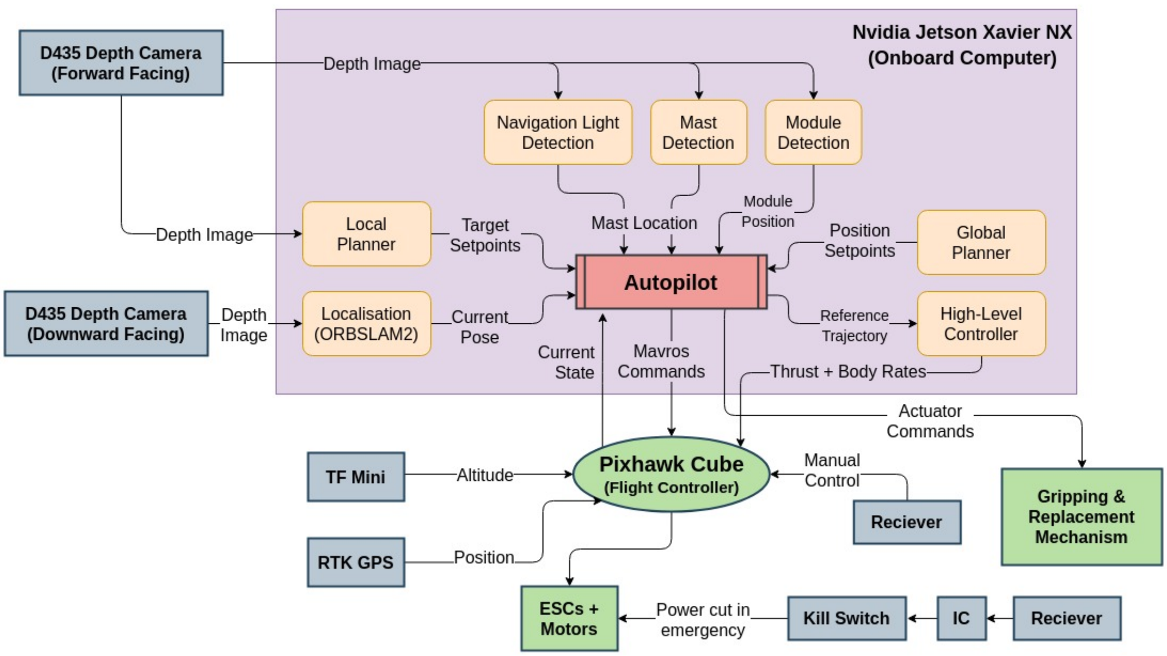


Figure 6. Control System Architecture

Guidance & Navigation (autopilot)

The mothership guidance system is responsible for carrying daughtership from the launch point to the mast location. This is done by navigating to-and-fro around the pylons. We use position setpoints with constraints on max velocity, max acceleration, max roll and pitch angles to maintain the center of gravity of the mother-daughter system for stable flight. After completing the laps, the mothership stably hovers and the daughtership takes off from it. Once the daughter ship moves away to a safe distance, the mothership returns to the launch site after navigating 8 laps around the pylons.

Daughtership guidance system works alongside with AI module that detects navigation lights to compute the orientation of the mast. The daughtership aligns itself with the mast accordingly. The AI module detects and continuously tracks the communication module as the daughtership aligns itself with the swaying mast.

Pixhawk flight controller along with PX4 [5] firmware is used for navigation. A custom Finite-State-Machine is developed as central Autopilot responsible for decision making and governing mission flow. The commands are sent by Autopilot using MAVROS, a ROS node that uses MAVlink protocol for communication between onboard computer, pixhawk, and ground control station and among the modules.

To estimate the spatial state of the system, RTK-GPS and visual SLAM are used. Data from Inertial Measurement Unit (IMU), 1D Lidar is fused along with the estimated pose using the extended Kalman filters to further improve accuracy. This state data is then published to the PX4 flight stack using MAVROS.

High-Level Controller
A custom high-level controller, capable of accurately tracking a trajectory [6], is currently being developed. A minimum-snap polynomial is generated, path passing through a sequence of 3-D positions and yaw angles while satisfying the constraints on velocities, accelerations, and inputs. This sequence of polynomial segments is jointly optimized to join those way-points into a smooth minimum-snap trajectory [7] from start to goal. The Trajectories can be obtained efficiently as the solution to a Quadratic Program that minimizes a cost function of the path derivatives as given below:

$$J = \min \int_{t_0}^{tm} \left(\mu_r \left\| \frac{d^4 r_T}{dt^4} \right\|^2 + \mu_\psi \left\| \frac{d^2 \psi_T}{dt^2} \right\|^2 \right) dt$$

Where, μ_r and μ_ψ are constants that make the integrand non-dimensional, r_T is reference x, y, z of the trajectory, ψ_T is reference yaw, t_0 and t_m are start and end timestamps.

The future plan is to modify the high-level controller using nonlinear controllers like Backstepping and Sliding Mode Control. This will make the controller robust to external disturbances caused by wind or reaction forces caused during docking and replacement of the communication module.

Flight Termination System (FTS)
The Flight Termination System is necessary if the quadrotor behaves in an undesirable manner. The FTS will be triggered in one of the following cases:

- **Mission failure of the system:** The return to launch command can be executed through the ground control station if 9 minutes have elapsed since takeoff. A human pilot can also take control of the quadrotor whenever needed.
- **Non-critical failure of the system:** The FTS will initiate controlled safe landing at it's current location, if connection to GCS is lost or battery voltage drops below a threshold.
- **Critical failure of the system:** The power to the motors can be cut via the kill switch in case of loss of control or departure from the mission area, causing the vehicle to shut down and fall. It can be remotely activated by the judges. A loss of signal to the remote activation system will also cause kill switch activation.

MISSION PACKAGE

Perception System

- When the Daughter drone is moving towards the mast, the communication module's orientation is not known. First, the navigation lights are detected. There are two lights (red and green) attached to the mast as seen in Figure 9c. The 3-D coordinates of both the red and green navigation lights are estimated.
- The Daughter drone then approaches the mast from the direction of communication module. While approaching, the blue board (as shown in Fig 9a) on the mast is detected i.e. the coordinates of the bounding box are estimated.
- When the Daughter drone is within a radius of 50 cm of the mast, module detection is initiated and continued until it is removed.

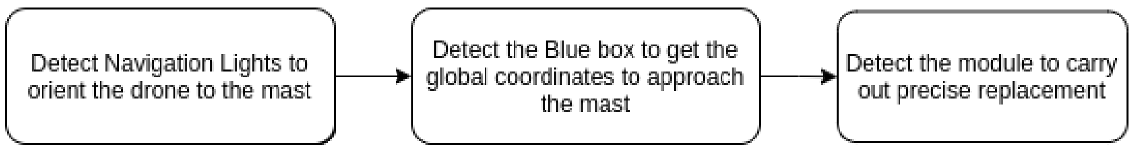


Figure 7. Perception Pipeline

Navigation Light Detection

For navigation lights detection, OpenCV's [2] color thresholding algorithms are applied on the hue dimension of HSV space to mask out the particular colour. Then a saturation threshold of > 200 is applied. Next, OpenCV's closing operation is applied to fill the broken parts in the object. The largest contour, in terms of the area, is picked from the list of contours given by the OpenCV's contour finding algorithm.

From this, centre of the individual lights is obtained as the centre of contours. Depth data from forward facing RGBD camera is used to get the 3D-coordinates of the lights in the camera frame and then which are then transformed to world frame.

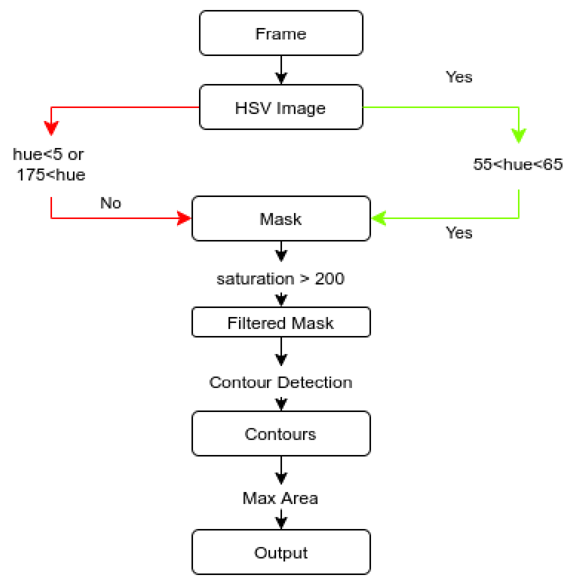


Figure 8. Navigation Light Detection

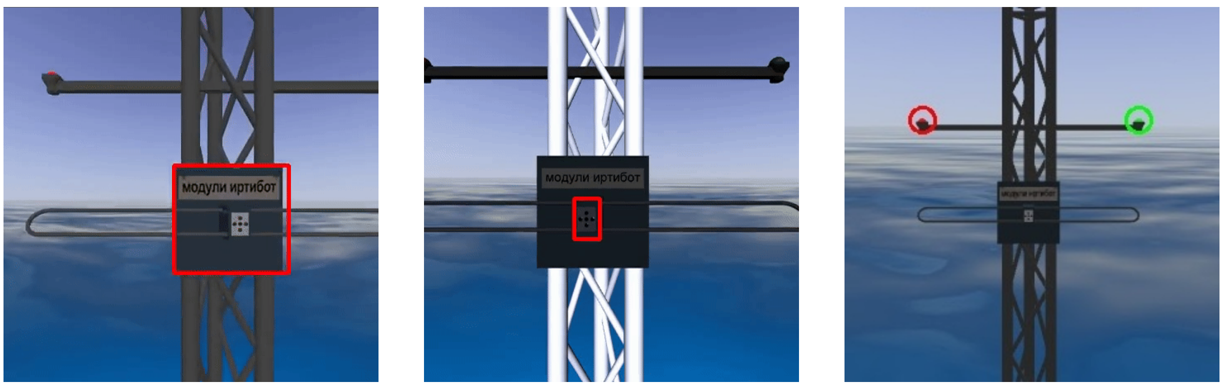
Mast and Module Detection

Using the approach in the previous section, location and orientation of mast is obtained. Daughter drone then approaches the mast from the direction that module is facing. While approaching the mast, the blue board on the mast is detected i.e. the coordinates of it's bounding box are obtained. For this, a Deep CNN architecture is used. To run the model in real time two stage model like RCNN [3] doesn't serve the purpose because it first produces thousands of bounding boxes and then classifies each of those. Among the single stage detectors, state of the art YOLOv4 [1] was chosen.

YOLOv4 takes the image and directly outputs the class scores along with bounding box predictions. It uses many advanced Deep Learning techniques like Cross Stage Partial connections, Mish activation, Complete IoU loss, mosaic data augmentation. It gives 43.5% mAP on COCO dataset and runs at $\sim$ 65fps on Tesla V100.

A dataset with around 2000 images of communication module and mast was created by simulating the mission environment in Gazebo. To get a diverse dataset, video feed of drone was used, with varying distances, heights and viewing angles.

Landing site detection
When mother drone comes back to starting point, we detect the base to land on. Colour threshold and pre-processing algorithm similar to Navigation Lights Detection is applied and then OpenCV's ellipse fitting function is applied to get landing site coordinates.



(a) Mast Detection : ML model is detecting the blue board in the mast

(b) Module Detection : ML model is detecting the communication module

(c) Light Detection : OpenCV algorithms detecting the two navigation lights

Figure 9. Outputs of the detection algorithms

Localisation

Daughter Drone
The daughter drone performs the task of aerial robotic arm manipulation/repair, hence we require it's precise localisation. A Visual SLAM (Simultaneous Localisation and Mapping) system, ORB-SLAM2 [8] is used. The data of IMU (Inertial Measurement Unit), 1D LiDAR for altitude and SLAM is fused using an extended Kalman filter to improve accuracy.

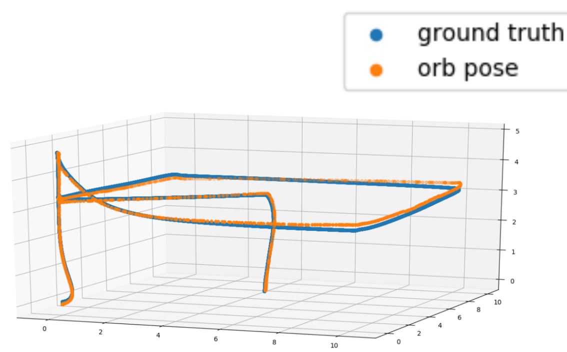


Figure 10. The estimated pose vs ground truth

Mother Drone
The mother drone travels at 15 m/s to cover a total distance of 6 Km in under 9 minutes. A standalone GPS can give accuracy of upto $5-7$ m. The signals used by standard GNSS receivers measure the time taken by signal to travel from satellite to receiver. But these signals could be potentially slowed down and perturbed when traveling through ionosphere hence it's performance is weather dependent. RTK-GPS (Real Time Kinetic GPS) fixed solution with at least 5 common satellites provides an accuracy range of 2cm [10]. It uses a base station set up at known location

and a receiver that gets corrections from the base station or a network of base stations. Once the base is established, it's job is to send corrected signals to the receiver.

Communication

The mission requires communication with the UAVs throughout the run to monitor their status and collect useful data. A telemetry module is being used for this, which allows us to link a flight controller to the USB or UART-equipped ground station computer.

We have a mother-daughter configuration, which requires the UAVs to communicate with each other at critical points of the mission. The solution is to establish this communication between the UAVs through a common WiFi channel stationed at the ground station. An 867 Mbps 23 dBi Outdoor WiFi Antenna is used. It gives a comfortable communication range of 5+ km with the UAVs.

MAVLINK [4] is used for communication protocol along with ROS (collectively called MAVROS), to communicate between the PX4 Firmware and the FCU.

RISK REDUCTION

To ensure the safety of the vehicle, a kill-switch is added and installed protective casings on all components to safeguard them against any damage in case of a potential collision. Routine inspections are conducted to ensure that all components are in working condition and the vehicle is only permitted to fly once it is deemed secure.

Safety

To ensure safety, the following checklists are used:

Pre-Flight Checklist:

1. The physical condition of the vehicle is checked to warrant that there aren't any loose parts or objects in danger of being hit by the propeller.
2. The transmitter is prepared to ensure flight termination via the kill switch. Electrical systems are checked for any possible breaks in connections.
3. The RC transmitter is switched on.
4. The battery voltage is examined on the RC controller screen for a full charge.
5. The vehicle is powered up.
6. Wifi connection is established between onboard computers and the ground station.

Takeoff Checklist:

1. A safe distance is ensured between the people and the vehicle, along with a safety net.
2. Autopilot is connected via MAVROS and the ground station computer is booted up.
3. Transition from RC controller to the offboard computers is offered.
4. Takeoff command is issued and autonomous mode is initialized.

Landing Checklist:

1. The landing site is checked for any kind of obstructions.
2. The vehicle is landed smoothly once the landing site has been inspected.
3. The flight controller is deactivated using the RC controller.
4. The onboard computational units are shut down and batteries are removed.

MODELLING AND SIMULATION

Software-in-the-Loop Simulation

At each stage of development of the multi-rotor system, individual aspects of mission are tested and validated in a simulation environment, Gazebo. Gazebo was chosen because of its low fidelity, but sufficiently accurate physics engine.

Testing of individual subsystems

Standardized tests are developed for quick iterations and validation of each subsystems' tasks. Larger integration tests are conducted for multiple subsystems to be tested in the simulation in a variety of environment conditions, validating robustness of the system. After successful implementation of major integration tests in Gazebo, same tests are run on real vehicle to check their reliability in real flight conditions. For various mechanical components like the custom gripper and the replacement mechanism, CAD files are converted to SDF models, and imported in Gazebo. The Joint Controllers are simulated using ROS, and their movement and function are simulated and validated, after which the actual gripper mechanism is manufactured and tested.

Testing of complete mission

After major integration tests are validated in the simulation, different environmental conditions like wind, and oscillation due to waves are added to simulation environment, and complete mission tests are performed in Gazebo, validating the desired parameters of each of the subsystems, even in extreme conditions. Full mission hardware testing is only conducted after the complete mission simulation tests are positive.

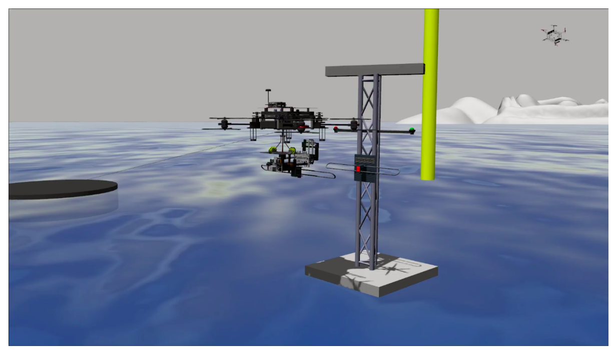


Figure 11. Testing of complete mission

Results

Owing to multiple simulation tests conducted, the reliability and time efficiency of the proposed system can be validated to be below the prescribed limit (9 minutes). The visual localisation system accurately predicts the current location of the drone with an accuracy of *3 cm* and ML models run at ∼30 fps on Nvidia Titan xp. The system is also successful in replacing the communications module with the reliability of around 90%, even in the Sea-State 3 level of mast deviations, and in at most 4 m/s windspeeds, while using 60% of daughter-drone power.

CONCLUSION

The system presented in this paper is a possible viable solution to challenges presented in the IARC Mission 9 statement. Rigorous simulation tests indicate that autonomous takeoff and landing, autonomous flight and remote module manipulation can be reliably used to complete the 2022 IARC Mission 9 hardware challenge.

Currently, the team is actively pursuing the IARC Mission 9 Hardware challenge 2022. The specific systems on hardware are being tested and modules like mechanical design and controls are being ideated and improved to perform better and to handle uncertainty while facing the various environmental parameters during the run.

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