Development of an autonomous aerial vehicle using Laser range finder

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ABSTRACT

Team Swift of Indian Institute of Technology Madras is participating in the 20th edition of International Aerial Robotics Competition conducted by the Association for Unmanned Vehicle Systems International. The complete problem statement is that the robot has to search an indoor arena for a pen drive kept in a box, acquire the original pen drive, replace it with a fake one and bring back the original one. The vehicle has to avoid a series of laser beams during the mission. The approach to the solution involves a Quadrotor helicopter enabled with a combination of Stability Augmentation System for stability, Simultaneous Localization and Mapping for positioning, Navigation and Image processing for object detection. Extensive multi-disciplinary work is involved in solving this problem statement.

INTRODUCTION

Statement of the Problem

An autonomous aerial robot which weighs under 1.50kgs and with a maximum dimension of 1m x 1m x 1m should enter an arena through 1mx1m opening and retrieve a pen drive and replace it with a duplicate pen drive. The aerial robot has to exit the arena with the retrieved pen drive. The pen drive is present in a room which is protected with a laser barrier and an alarm sets off if the laser beams are interrupted. The laser barrier can be manually turned off using a mechanical switch after which the aerial robot can enter without detection. At the 1mx1m opening is a blue led, which simulates a camera and switches on and off alternatively every 30 seconds. The mission is said to be completed if the pen drive inside the arena is retrieved. The whole mission is termed as clean if it is done covertly else it is termed as dirty if it is detected by any of the sensors. Failing to drop the duplicate pendrive in place of the original pendrive would also be deemed as a dirty mission.[5]

Conceptual Solution

Quadrotors are not stable by themselves. So we need a Stability Augmentation System (SAS) to keep the quadrotor horizontal. We are using an open source quadrotor called Mikrokopter[1]. The vehicle is equipped with a Scanning Laser Range finder. The data from the Scanning Laser Range finder is processed in the on board computer to get the position estimate which in turn is used for stabilizing the position of the quadrotor. A collision avoidance routine makes sure that the vehicle does not hit any obstacle. The image data is processed on the ground computer to see if the desired target (pen drive in box) is in view and computes the direction to move if the target is present. The mission planning algorithm oversees all the above modules and acts as required.

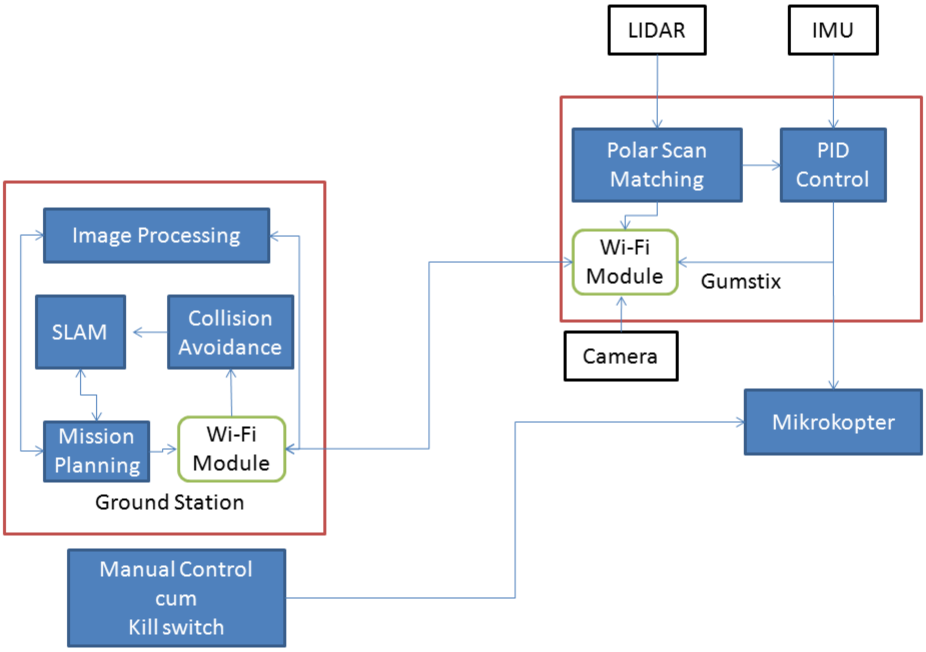

Figure 1: Overall system architecture

Yearly Milestones

In the year 2010, our team has set a goal to enter the arena and navigate in the arena while performing collision avoidance. We are now working on image processing and object recognition separately. In the year 2011, we would be in a position to integrate the image processing module with the robot and search for the pen drive. We also aim to develop a mechanism to acquire pen drive by the year 2011. We also plan to work more to make the position stabilization better as it would be essential for acquiring the pen drive. Thus we aim to solve the problem statement by the year 2011.

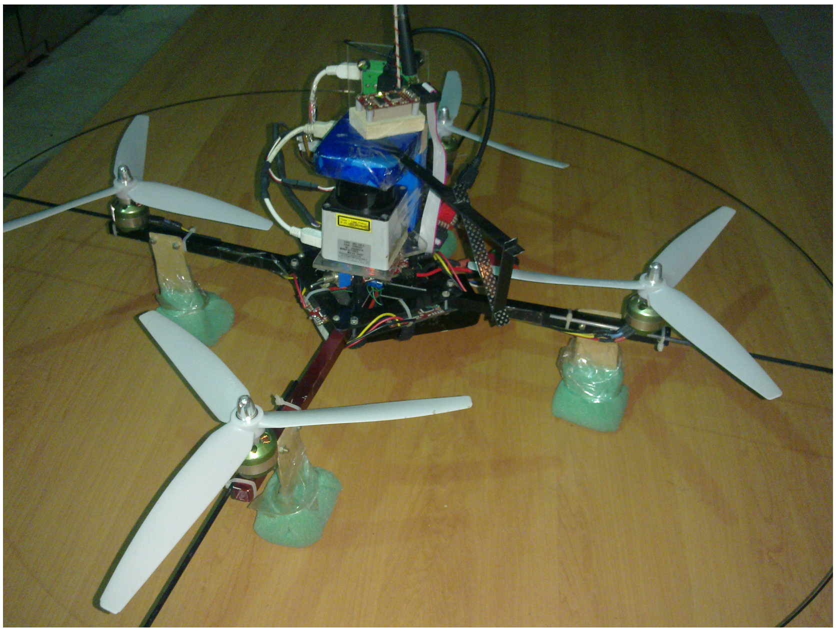

Figure 2: A picture of the quadrotor system

AIR VEHICLE

Propulsion and Lift System

The quadrotor is an aerial vehicle with four rotors fixed at four ends of a square. It is controlled by changing the RPM of each of the motors on to which the rotors are mounted. The rotors placed opposite to each other rotate in the same direction. Torque on the body can be made zero by having a set of two rotors rotate in clockwise and the other set in anti-clockwise direction. The propellers are such that thrust from all rotors is upwards and almost equal. Previously we have used X-3D-BL scientific from Ascending technologies as the base vehicle. The base platform, which has now been changed to Mikrokopter is an open source platform with access to the source code. This was done for two reasons, viz. the inability to change the motors in X-3D-BL Scientific and the flexibility an open source platform offers at later stages due to the access to source code. The arms of the mechanical frame are made of hollow aluminium bars. The Central frame is made out of carbon fibre. This frame encases the electronic circuits. A mount is constructed out of perspex sheet to accommodate the LIDAR.

Stability Augmentation System

The quadrotor is not an inherently stable aerial vehicle. It needs an active stabilization system. The previously used base platform X-3D-BL scientific has an on board stability augmentation system which maintains the stability of the quadrotor. The inertial measurement unit on board consists of a three axis accelerometer, three rate gyros and a magnetic compass. An Atmega processor calculates the tilt angles using the data from the accelerometer,

gyros and the magnetic compass. A PD control loop calculates the required input needed to keep the quadrotor stable using the tilt values. The present quadrotor is Mikrokopter which uses PID control loop. The control loop similarly uses the tilt values calculated by the IMU and stabilizes the quadrotor. The new quadrotor behaves better in case there is a small offset in the distribution of masses on the quadrotor. The presence of the integral constant makes this possible.
The motion of the quadrotor is controlled by changing the set point(the values of pitch and roll) at which the quadrotor is staibilized. When a control input is given the PID control loop tries to stabilize the quadrotor at the desired control point. For instance by giving a certain pitch the PID control loop stabilizes it at the pitch input given.

Guidance Navigation and ontrol

Navigation

Our Navigation system consists of four modules namely, Drift control system, Collision avoidance system, SLAM system and Mission planning system

Drift Control

Any aerial vehicle when left uncontrolled is subject to drift in position. This drift of aerial vehicle becomes more important in indoor arenas. A position feedback is needed to maintain the position. GPS is unreliable indoors because of which alternative positioning methods need to be used. In our system, we use a Scanning Laser Range finder and process the scans using scan matching and obtain the relative position of the robot with respect to the set point. Drift control demands minimal latency possible between the occurrence of a motion and the recognition of the motion in the on-board computer. This requires the scan matching algorithm to be computationally light in nature. Hence, we use an algorithm called Polar Scan Matching[4] which has the above features.

In polar scan matching we use a iterative loop to converge the orientation and translation to a ground truth value.
The following are the steps involved in polar scan matching approach
Scan preprocessing: A median filter is applied on the scan data to remove any erroneous data, poles and other features which may present an ambiguity in the matching process. The scans are then segmented if they are farther than a threshold as compared to its nearest neighbours and they don't lie on same line.
Scan projection : The current scan is translated into the reference frame of the initial scan assuming zero displacement and rotation. Iteratively these positions are updated to arrive at a lower least square error.
Occlusion Filter : The current scan after translation can give some scan data which may not be visible from the reference position. Then the occlusion filter is applied to remove these data and replace them with reference range.
Orientation : The translated scan and the reference scan are now compared through a search for least square error in a specified window size.

Translation : The translation is done using by applying the polar transformation matrix on the polar distance differences of the translated and reference scan with the elements weighted according to distance differnces. This gives higher preference to the closer points.

To suit our choice of laser scanner and with our limited onboard processing power we made some changes to the algorithm.
The weights and other parameters were modified to suit our laser scanner's range and field of view.
Fusion of data from the magnetic compass to help the orientation algorithm converge faster.
Insertion of previous position estimates to the translation to converge faster.
Raising the convergence limit so as to get an optimal latency and accuracy required for good drift control.

Using this algorithm, we compare the present scan with the scan whose center is the position where we want the robot to stabilize (i.e. set point) and obtain the relative position of the robot with respect to the set point. We apply a PID Control (Proportional-Integral-Derivative Control) on the position thus calculated. We use the translational acceleration data from the on-board IMU along with the scan matching data to compensate for latency. The Pitch and Roll given to the robot according to the PID algorithm can be expressed as follows:

$$Control_{Pitch}(t) = K_p * error_x + K_i * \int error_x dt + K_d \frac{d(error_x)}{dt} + K_{ax} * acc_x \tag{1}$$

$$Control_{Roll}(t) = K_p * error_y + K_i * \int error_y dt + K_d \frac{d(error_y)}{dt} + K_{ay} * acc_y \tag{2}$$

where K_p, K_i, K_d are the gains of proportional,integral,and derivative controls respectively.
K_{ax}, K_{ay} are the gains of the translational accelerations in X and Y directions respectively. These components compensate for the latency of the LIDAR data. $error_x, error_y$ are the position errors in X and Y directions with respect to X and Y of the set point.
acc_x, acc_y are the translational accelerations in X and Y directions respectively
Incremental motion of the robot is possible by changing the set-point value of the PID algorithm and updating the reference scan as soon as the robot reaches the new set-point.[6]

Collision Avoidance Algorithm

A Collision avoidance routine is implemented every 0.5 second to ensure that the robot does not hit any obstacle and traverses through the arena safely without hitting the walls. Every 0.5 second, the LIDAR scan is taken and the farthest distance that the robot can go forward without hitting the walls is marked. The collision avoidance algorithm finds a suitable point in this maximum distance direction and sets it as set-point to the drift control routine. The drift control system maintains the robot position around this point and thus avoids the robot from colliding with the walls. The collision avoidance system is free running in the sense that, with only the collision avoidance system running (without mission planning), the robot just explores the arena without concern of whether it has explored that region earlier. The obstacle avoidance algorithm used in our system can be represented as follows:

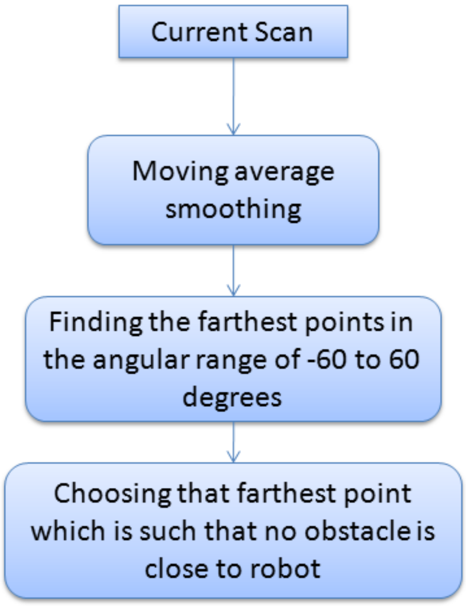

Figure 3: Flow chart of collision avoidance system

SLAM (Simultaneous Localization And Mapping) Module

The position calculated by the Polar Scan matching algorithm in the drift control module is suitable only for position stabilization at a point. It cannot be used for continuous positioning as it is prone to accumulated errors. We need a fully developed SLAM algorithm for this purpose. We use ICP(Iterative Closest Point) based SLAM algorithm from MRPT library (Mobile Robot Programming Toolkit library)[2] for localization and mapping. As SLAM is a computationally intensive process, it cannot be done on-board. Hence, the scans are transmitted to the ground station via WiFi link and SLAM is performed.The map, the path taken and the current position are used for the higher level Mission planning module.

Mission Planning module

This is the highest level module of the system. This module checks if the path suggested by the collision avoidance algorithm has already been taken and overrides the collision avoidance system if the path has already been taken. It also takes care that the robot does not fly around the same place in case of a dead end.

PAYLOAD

Sensor Suite

Hokuyo URG-04LX Laser Range Finder

It is a 2D laser range nder with a range of 4m and a eld of view of 240degrees.This sensor is used for position calculation and thus stabilization, mapping and collision avoidance. It has an update rate of 10Hz. This value along with the onboard IMU is used in position stabilization.[3]

Inertial Measurement Unit (IMU)

The quadrotor that we are using has three axis gyros and accelerometers which provide the acceleration and tilt data to the on board computer. The update rate of the IMU is 50 Hz. The acceleration data is used to reduce the latency of the position estimate got from Polar scan matching.

Camera

We have an on board camera which transmits pictures frame by frame to the ground station over WiFI link. We are yet to incorporate this into our system. Once finished, the data from the camera will be used for detecting the box containing pen drive and the Arabic symbols.

Image Processing

Presently, the image processing work is being done off the vehicle. It will be integrated onto the vehicle once the rest of the system becomes ready.
Our image processing work can be broadly classified as:
1. Classification of Arabic phrases using Pattern Matching
2. Object Detection using Machine Learning

Classification Of Arabic Using Pattern Matching

The objective is to differentiate between 3 Arabic phrases:
For this, the camera image is first converted into binary image. Transformation functions are used to achieve invariance in scale. Rotation invariance is achieved by changing the co-ordinate system from the usual Cartesian to Polar coordinate system. The unique features of the phrase are matched with the templates to differentiate between the phrases.

Object Detection

According to the problem statement, we need to detect a box and a pen drive kept in that. We are using HAAR training Machine learning system to detect these things. In this method, we first extract feature data from images.We are using mathematical functions to form feature vectors . Haar- Training is done for these feature vectors. A detection module which matches the incoming data with the 'Training file' is implemented.

Threat Avoidance

The aerial vehicle is outlined with a circular frame made of light weight Carbon fiber rods. This structure ensures that the propellers do not hit the arena in case of mishaps.

Communication

There are four main communication links. The first is between the kill switch cum manual control and the vehicle. This is a 72 MHz frequency modulated RF link. The data is transmitted at a rate of 50 Hz over this link. The second is between the vehicle and the ground computer. This is an 802.11g 2.4GHz wireless link established using a Wi-Fi module integrated with the Gumstix Overo board.
The third and fourth communication links go through a common USB hub.
The third link is a Serial link from the Gumstix to the Mikrokopter base board. This uses an FTDI chip to connect to the USB hub. The fourth is a direct cable which connects the LIDAR to the USB hub.

Power Management System

A 11.1V Li-Po battery is used to power the motors and the electronics onboard. A switcher circuit is used to convert this voltage to 5V DC. This reduced DC voltage is given to the Gumstix board and the LIDAR. A switcher is chosen instead of a voltage regulator so as to minimize heat losses. A low voltage detection is implemented in the quadrotor making it auto shut down once the battery voltage drops below 8 Volt.

Flight Preparations

Preparation Before Entering The Arena

Charge the transmitter battery. Charge the aerial vehicle battery Check if the WiFi link is established. Recalibrate the Magnetometer and gyros. Check if the height value from LIDAR is correct.

Preparation After Entering The Arena

Check if all the inter process communications are happening properly. Check the connectivity of LIDAR. Check the accuracy of X and Y values. Check if the automatic switch on the transmitter is switched on. Check if the manual limit on throttle is set to maximum.
After each flight, the structural integrity of the vehicle is to be checked.

Man/Machine Interface

Time tagged position and velocity status messages are transmitted to the judges Common Operating Picture (COP) using JAUS compliant messages. The mission is started when a Resume message is received from the judges COP. The mission is terminated when the target is identified or if a Shut- down message is received from the judges COP. For emergency shutdown of the vehicle a manual kill switch is activated causing the vehicle to land immediately.

RISK REDUCTION

Vehicle status

The battery voltage, position and the control signals (Pitch, Roll and thrust) given to the quadrotor are sent to the ground computer for continuous monitoring. A real time graph of position and the individual components of PID control is plotted. The map and the position output of the SLAM algorithm are also plotted. Also, the vehicle sends information about any collision that may have happened on the way.

Shock/Vibration isolation

The vehicle is outlined with a circular carbon fiber frame which protects the vehicle and its propellers from direct impact of shock. The vehicle is also provided with a spongy landing gear to protect it from shock caused due to sudden landings.

EMI reduction

The Magnetometer which is crucial for holding yaw is very sensitive to high currents in its vicinity. Hence it is placed on top of the LIDAR, far from the electronics and power wires.

Safety

The LIDAR is covered with a Styrofoam casing which protects it from crash landings. The propellers are protected by the circular carbon fiber frame. The nuts and bolts are made of plastic to prevent inadvertent short circuits in case one of them gets out and falls on the circuit boards. The landing gears are designed such that in case of extreme crashes, they take the complete impact by breaking and thus stop the impact from passing.

Modeling and simulation

We modelled the system in Simulink to find out the optimum PID gains before testing them on the actual system. Simulation is also done to estimate the maximum latency that can be allowed in the system for acceptable position stabilization performance. Presently, we are working on using Simulink for simulating the complete system. Matlab was also extensively used for developing the collision avoidance algorithm. The algorithm and its parameters were fine-tuned using Matlab first and then implemented in C.

Testing

We achieved position stabilization using Polar Scan matching and PID control. The robot can stabilize within a circle of 20cm diameter. Incremental motion of the robot has been tested where the robot was made to move in steps of 5cm in desired direction. The collision avoidance algorithm has been tested separately on a ground robot. The obstacle avoidance algorithm will be incorporated on the Aerial vehicle soon.

CONCLUSION

We have developed an autonomous quadrotor capable of exploring indoor arena. It is also capable of avoiding collisions with walls and obstacles. We have achieved incremental motion of the quadrotor. The quadrotor has an increased payload and time of flight as compared to our previous attempt. Many problems caused due to limited computation power were solved by using and developing efficient algorithms. Work on object detection is being done and we will be in a position to integrate it into the system soon.

Acknowledgements

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