Dronolab 2013 technical paper on UAV design for indoor flight for the 23nd annual IARC competition

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ABSTRACT

This paper presents Dronolab's unmanned aerial vehicle (UAV) design for the 23nd Annual International Aerial Robotics Competition (IARC) organised by the AUVSI. It presents the many challenges of UAV exploration with no Global Positioning System (GPS). Dronolab's solution is based on laser rangefinder (Lidar) which, combined with a SLAM algorithm, tracks the position of the vehicle in its environment. A Kalman filter is used to fuse this positioning data with an inertial navigation system (INS) to improve the estimation of the UAV's position. Robust adaptive backstepping control is then used to control all 6 degrees of freedom of the UAV to track desired trajectory calculated by a mission manager.

INTRODUCTION

Statement of the problem

The main challenge of the competition is indoor navigation where the aerial vehicle is deprived of an important source of information which is normally provided by a GPS. The lack of an absolute position data implies that UAV must rely only on relative information.

Some solutions to this problem have already been developed for unmanned ground vehicle (UGV). Those solutions are typically based on precise odometry systems that use wheel displacement, INS and artificial vision. But few of these concepts have been successfully integrated on a UAV because they have more constraints. First of all, the odometry for a UAV cannot be based on a rotary encoder, which makes the system less precise. Secondly, energy and thrust limitations diminish the payload lifting capabilities of such robots, which limit the quantity and the quality of sensors that can be carried. Thirdly, the UAV, even in hover flight, may change position because of a change in air inflow, which makes it less stable than a UGV.

Another challenge is that the UAV evolves in an unknown and confined space which increases the risk of a collision. In order to minimize chances of collisions, the UAV must be as small and agile as possible. It must also rapidly detect and avoid obstacles during autonomous missions.

Conceptual solution to solve the problem

Choice of the aerial vehicle

One of the main characteristics mandatory to perform indoor exploration with an aircraft is the capacity to hover and to perform vertical takeoffs and landings (VTOL). Dronolab has chosen the quadrotor helicopter design for a few reasons. The agility of the VTOL design makes it an excellent choice for flights in confined space. Moreover, the multirotors' mechanical design is very simple as it uses fixed pitch propellers. This makes the multirotor easy to fabricate and repair compared to conventional helicopters. Finally, the quadrotor offers a great balance between payload capacity and size.

Choice for relative position system

A SLAM-like approach was chosen as the relative positioning system. This is detailed in the navigation section.

Technical choice

In order to maximize the processing power available, an off-board architecture has been selected. The data acquired by the drone's various sensors is streamed wirelessly to a ground station capable of computing large amounts of information in a short time. That station then takes a decision depending on the analyzed data. The result is then sent back to the drone and the process is repeated as many times as needed.

The weight limitation is addressed by using a fast prototyping manufacturing process which allows versatility in the design of the drone. A combination of carbon fiber and 3D printed plastic is used to achieve the maximum strength to solidity ratio. Further weight is reduced by optimizing the positioning of the components on the board and minimizing the number of fasteners used.

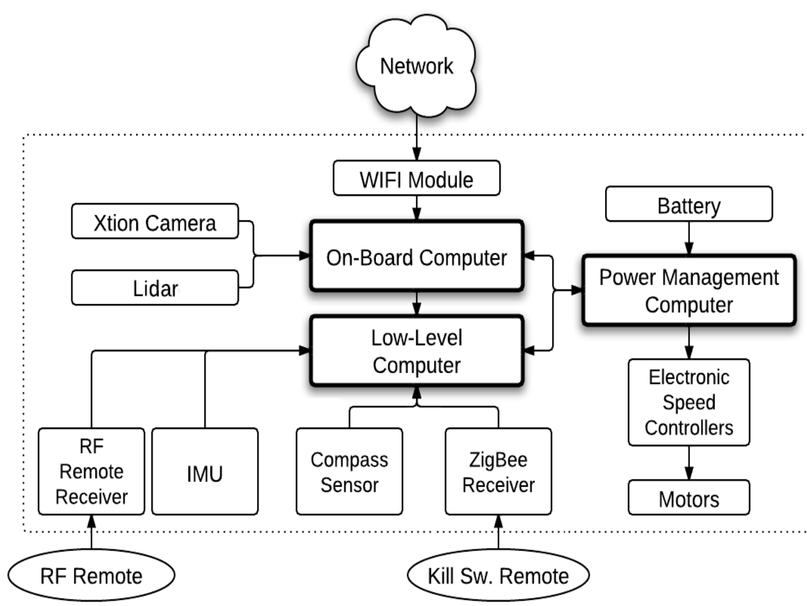

Figure 1. Hardware architecture

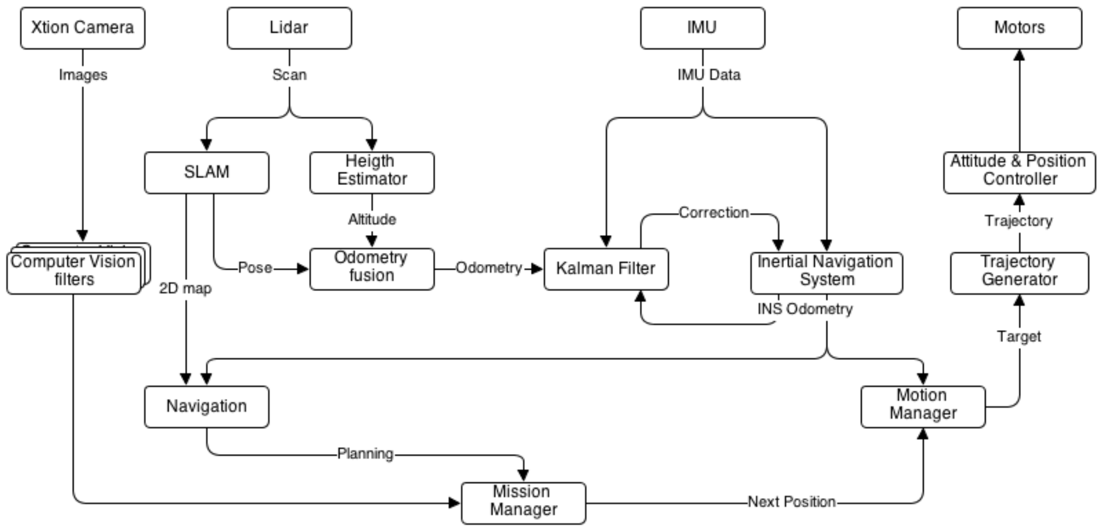

Figure 2. Software architecture

Yearly Milestones

This section illustrates the four milestones that have been fixed in august 2013 to organize the work during the year. Due to a major change in the team's organisation and a delay in the development, the initial planning of three years has been extended.

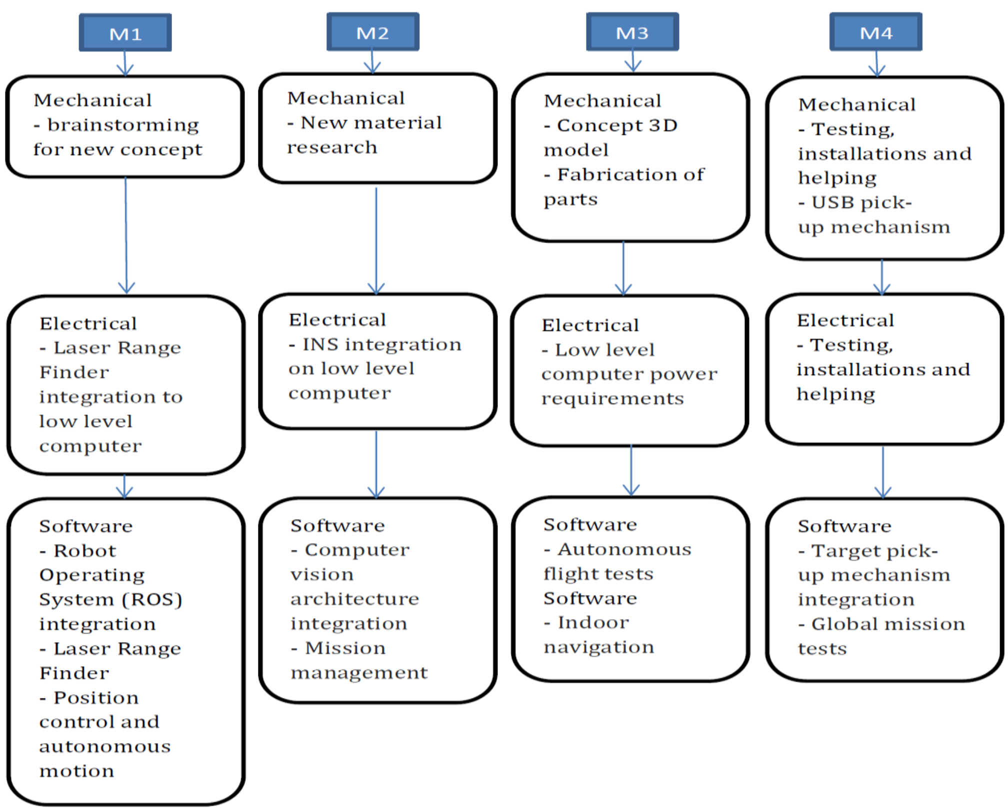

Figure 3. 2012-2013 Project milestones

AIR VEHICLE

Propulsion and Lift System

The two most important characteristics of motor/propeller combinations are the response time and the maximum thrust generated. The quadrotor's performances are directly affected by the motor speed as they are the only control input. During simulation runs, it was evaluated that a motor's time constant of 150 ms is the threshold in order to achieve good system performance.

Also, a fraction of the drone's maximum thrust must be reserved to allow it some maneuverability. In other words, there has to be a margin between hovering and maximum motor speeds so that a thrust can be used by the quadrotor to change its position and orientation. That margin was evaluated to be in between 40 and 45 percent through simulation.

Given the fact there is very little literature characterizing the performance of motors and propellers, Dronolab decided to do its own experimentation with nine motors and four propellers to determine the best motor/propeller combination according with the best time constant and maximum thrust margin.

Guidance, Nav., and Control

The 3 attitude angles (roll, pitch, and yaw) of the quadrotor are controlled by changing the velocity of different pairs of motors. The motors can rotate only in the direction specified by the arrow in the figure below.

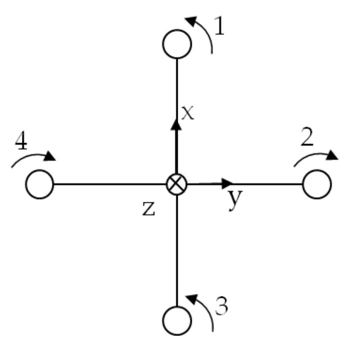

Figure 4. Quadrotor's body axis and direction of motor rotation

The roll (rotation around the x body axis) is controlled by the difference of thrust between the motor 2 and the motor 4. The pitch (rotation around y body axis) is controlled by the difference of thrust between the motor 1 and the motor 3. The yaw (rotation around the z body axis) is controlled by the difference of thrust between the pair of motor 1-3 and the pair of motor 2-4. The total thrust is generated by the combination of the 4 motors. The position is controlled by orienting the total thrust in the desired direction. Since this is done by changing the quadrotor attitude, this implies that the quadrotor is an under actuated system. In other words, the quadrotor possess less actuator then degrees of freedom that there is to control.

Stability Augmentation System

An adaptive integral backstepping controller based on the work of (Bouabdallah, 2007), (Madani et al., 2006) and (Krstic et al. 1995) was chosen. The backstepping scheme is well suited to this system because it has good perturbation rejection. Also, this type of control uses the system's natural nonlinear damping to assure stability. The integral and adaptive part of the controller corrects for the non-modelled dynamics and the parameters variations.

To design the controller, the dynamics of the quadrotor is simplified and decoupled for each axis. The aerodynamic effects are neglected, the thrust and drag force are modeled as proportional to the square of the motor speed and the motors are considered to be perfect.

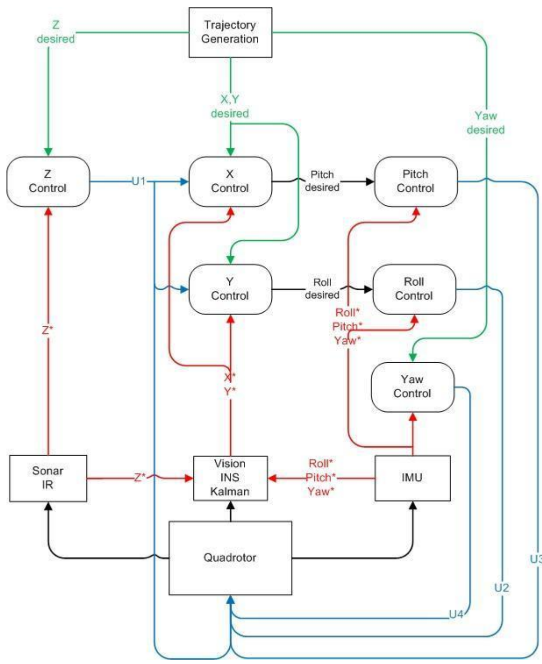

Figure 5. Nonlinear control architecture

The total control system is implemented as six single-input single-output (SISO) control law separated in 3 stages. The first stage control the altitude which computes the total thrust required (the command input U1). Then the control for x-y uses the total thrust and calculates its orientation in the second stage. This produces 2 virtual control inputs that are applied to third stage which control the attitude (roll, pitch) which the yaw controller commands. This last stage also calculates the other command inputs U2, U3, U4. A diffeomorphism then transforms the 4 control inputs (U1,U2,U3,U4) into the 4 desired motor speeds.

As the figure shows, all degrees of freedom of the quadrotor cannot be controlled directly. The complete system inputs are the trajectory describing the desired position (x,y,z) and orientation of the quadrotor (yaw angle). The stability of the attitude angle (roll, pitch) is assured, but cannot track a desired value.

Navigation

Typically, one of the systems used to perform relative navigation is an Inertial Navigation System (INS). An INS uses the linear acceleration and angular velocities measured by an inertial measurement unit (IMU) and integrates it to estimate position.

For a matter of weight constraints, the IMUs that are typically embedded on quadrotors are microelectromechanical systems (MEMS) based. This family of IMUs is well suited to measure UAV orientation but does not work very well with an INS. Indeed, the INS error, influenced by noise and bias, grows exponentially with time because of the double integration needed to transform acceleration into position.

Using other measurements for INS correction is one possible solution to counter the error of the system. Dronolab navigation architecture is based on two navigation systems : an INS and simultaneous localisation and mapping (SLAM) algorithm. The goal is to use the two systems and merge them with a Kalman filter in order to minimise the error produced by each sensor. Given that the SLAM system is much slower (1hz) than the INS (1 Khz), the Kalman filter is processed every time new information is available.

The navigation system architecture combines depth measurement sensors, onboard sensors, INS and off-board software that estimates the current UAV pose. The off-board processing is the pillar of the architecture and needs a lot of computing power to minimise delays with real time feedback. It performs SLAM alogrithm using 2D point cloud data from a lidar device. Once the current drone’s position has been determined through the SLAM process, a Kalman filter merges it with the INS attitude and position results. Consequently, the decision making system responsible for planning the next exploration trajectory is notified of new current pose estimation and interesting features detected. Those features are planes, end of planes, wall corners and windows. When ready, a navigation decision is sent back to the UAV.

Flight Termination System

Mosfets are connected to each motor power line and can be shutdown either by the microcontroller with a software command via the telemetry or physically with a switch mounted on the quadrotor. Also, a kill-switch is integrated on the remote control (RC) allowing shutdown of all four motors by bypassing the nonlinear controller and forcing a command of 0 to each motor.

PAYLOAD

Sensor Suite

GNC (Guidance, Navigation and Control) Sensors

The navigation system is based on 3 main sensors to estimate the UAV’s position. The most important sensor is the IMU unit. Miroirs on the lidar device are used to determine the altitude of the vehicule. The vision data is obtained with the Asus Xtion, which is a structured light 3D Scanner. Also, it has a regular camera allowing a wide array of applications.

IMU	3DM-GX3-25
LIDAR	Hokuyo utm-30lx
Vision	Asus Xtion Pro Live

TABLE 1. List of sensor embedded on the UAV

Target Identification Sensors

The window is detected using a computer vision algorithm on the depthmap produced by the Xtion device. A depthmap is an image where each pixel represents a distance value. An adaptive template matching algorithm based on geometric hashing is used to detect a square opening. The depthmap is transformed into a point cloud. On this point cloud, horizontal plane detection algorithm combined with an objects detection algorithm are used to determine position of desktop and objects. This way, we can match standard image detection with object position to find the flash drive.

Threat Avoidance Sensors

The SLAM algorithm allows obstacle avoidance by calculating a costmap for navigation use. A costmap is an area where the vehicule should navigate in the form of an occupancy grid. This way, the system cannot determine a trajectory which will produce a potential collision. Furthermore, the navigation system can react against unexpected drifting or mobile obstacles.

Communications

The system uses two main communication systems. The first one is a Zigbee transmitter which can be seen as a wireless serial port. This communication link is used to transfer telemetry data to the base station. This link can also be used to send a command to the UAV from the ground station. The second is a WIFI link that is used to transfer the visual data from the onboard to the off-board computers.

Power Management System

The power management system is based on a dedicated microcontroller which provides energy to the four motor controllers, the on-board computer and the low-level main controller. Its energy source consists of a single Li-Po Battery (11.1V, 4000mAh) which allows approximately 15 minutes of autonomous flight. Each motor speed-drive channel is equipped with a voltage and current sensor that effectively track the power consumption of the brushless DC motors at all times.

OPERATIONS

Flight Preparations

Checklist(s)

A pre-flight checklist has been developed in order to ensure the security of the pilot and potential bystanders. It begins with a physical checklist:

- Check RC radio transceiver connector
- Check 3DM-GX3-DM connection to UART2 connector
- Check WiFi transceiver connection
- Check Zigbee transceiver connection
- Check 4x motor controller connector
- Check OBC power connector
- Check 4x motor blade orientation

Once the physical checklist has been completed, a functionality test must be done:

- Program the UAV with the latest stable code
- Power on RC controller
- KILL switch in the ON position
- Auto/Manual mode selected based on flight mode
- Power on main control board
- LED indicators:
- MANUAL (ON/OFF) depending on flight mode
- UART 0, 1, 2, 3 and 4 for peripheral errors
- RC ERROR for RC remote connectivity problems
- Move throttle control on remote in predefined sequence.
- READY TO FLY when all errors have been cleared.
- RESET button will reset the whole system and initialize the motor controllers
- Visual and/or audio indicator will confirm the readiness of each motor.

Man/Machine Interface

The software system architecture uses the Robot Operating System framework allowing complete system data monitoring through several tools like rviz, rostopic and rqt plugins. Moreover, messages can be send directly via a publishing tool. A remote control (RC) can be used in manual mode to pilot the quadrotor.

RISK REDUCTION

Vehicle Status

Shock/Vibration Isolation

Vibration in the drone primarily comes from the motors and propellers. These vibrations cause noise in the attitude and position measurement of the sensors. Therefore it is important to reduce vibrations in the drone as much as possible. The first step taken was to balance the propellers on a custom built test bench. Then, during the motor tests, the vibration produced were measured and taken into account into the selection criteria. Also, since the drone’s frame is built out of plastic, it absorbs part of the vibrations produced by the motors.

EMI/RFI Solutions

The intrinsic design of the low level controller main board was set upon minimizing EMI/RFI. Due to the numerous components, relative area and design complexity, we opted for a four layer printed circuit board. In doing so, this allowed us to allocate one whole layer as a ground which in turn minimized the ground trace routes. The effect of having a complete ground plane isolates Tx/Rx communications between the top and bottom layers. There is also the effect of creating a low pass filter thus blocking high frequency noise. This is due to the capacitive effect of the ground plane.

Our previous design made use of the I2C hardware communication protocol between the main low level controller and the electronic speed controllers (ESC). Cabling length between the LLC controller and ESC was above regulation length. This fact introduced some unexpected anomalies such as I2C link failure in pre-flight and inflight. The final solution was to change the communications media altogether. We opted for PPM (Pulse-Position Modulation) controlled electronic speed controllers which would theoretically ensure a more stable and interference free communication.

Safety

The primary safety system consists of a kill switch, located on the main 2.4 GHz remote control, which can instantaneously kill all four motors. Also, a software emergency stop command can be sent through the Zigbee communication channel. Furthermore, there are several software emergency states programmed on the low-level controller that will shut down motors if the roll or pitch exceeds a safety value.

To ensure a secure start-up routine, a few more steps have been added. A software switch controlled by either the ground station or remote control actively enables/disables the one power MOSFET driving all motors on the drone. The throttle stick on the remote control must be moved in a predefined sequence in order to set the drone in READY mode. The drone cannot function, even when powered, without establishing a connection with the remote control. This functionality cannot be overwritten by the ground station.

Mechanical parts have been designed to protect the electrical components. The external parts such as the arms and the battery case were designed to break in order to absorb as much kinetic energy as possible in case of an accident.

Modeling and Simulation

A fully modeled nonlinear dynamics of the quadrotor is available in Matlab/Simulink environment. The simulation has been used by the controller designer to develop and test the control algorithm and to tune the controller gain.

A high level simulation model named Gazebo is used for navigation simulation. This simulation provides a 3D generated environment which use simplified quadrotor’s dynamics but fully model of every onboard devices like cameras, lidar, sonar, etc. This allows Dronolab to test artificial vision algorithm and the mission manager.

Testing
All flight tests have been made in a secured area based on the concept of the flying arena of the ETH. The test facility is a 14'X14'X5' area surrounded by a net to prevent the prototype from hitting hard surfaces.

The secured flight space has been built to prevent an eventual break of material caused by flight crashes. It has been designed to prevent any damages to the drone from a 3.5 meter fall. It is fully modular and can support inside panels to simulate competition's conditions.

Many software testing tools have been developed to monitor system performance and for debugging applications. Those tools include a logging system that saves telemetry data into dedicated files that can be consulted when needed. It also includes a replay device that uses saved data to mimic the UAV and devices for other part of the system.

CONCLUSION

In this paper, Dronolab detailed its conceptual solution to design a UAV able to perform exploration of unknown indoor environment. The UAV's payload is described in detail. Also, the design of a navigation system based on 3D vision and INS data is explained. Risk management, debugging system and flight operation are also presented.

Many features are yet to be tested or implemented, but Dronolab's team is confident that their approach will be a success in a near future.

REFERENCES

Bouabdallah, Samir. 2007. «Design and control of quadrotors with application to autonomous flying». Thèse de doctorat no 3727, École Polytechnique Fédérale de Lausanne. 155p.

Madani, Tarek et Abdelaziz Benallegue. 2006. «Control of a Quadrotor Mini-Helicopter via Full State Backstepping Technique». In Proc. (IEEE) 45th Conference on Decision & Control (San Diego, Dec. 13-15 2006), p.1515-1520.

Krstic Miroslav, Kanellakopoulos Ioannis, Kokotovic Petar. 1995 «Nonlinear and adaptive control design». Wiley Technology & Engineering, 563p.