Towards Open-Source, Printable Pico-Quadrotors

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I. INTRODUCTION

The past decade has seen an increased interest in Autonomous Micro Aerial Vehicles (MAVs). Rotary wing MAVs such as quadrotors, can operate in confined spaces, hover at any given point in space and perch or land on a flat surface. This makes the quadrotor a very attractive aerial platform with tremendous potential. Our main goal was to design and prototype an MAV that weighs less than 30g and is capable of fully autonomous flight.

In this study, we investigate the added benefits of scaling down, such as a significant increase in agility of the robots and their ability to operate in tight formations for flying in confined spaces. Building on our previous work of implementing various methods of rapid-prototyping to design and manufacture small quadrotors[1], we took a monolithic design approach for the Pico-Quadrotor, and the multi-purpose use of as many components as possible. The resulting quadrotor weighs 25g with battery, can carry a payload of about 10g, is capable of autonomous wireless recharging and capable of reaching top speeds of 6 m/s in a 2 m × 2 m × 3 m flight space. These Pico-Quadrotors span a little over 4 inches in diameter and have been flown in a four robot delta formation at speeds of about 3m/s.

II. SCALING

Scaling has a tremendous effect on the dynamics and physical properties of the quadrotor. These properties include mass, linear and angular velocities, inertia, flight-time etc. We define the characteristic length of the robot as \( L \). By scaling down the size of the robot, we see that the mass \( m \) scales as \( L^3 \), and the moments of inertia as \( L^5 \). Considering that the rotor radius, \( r \), scales linearly with \( L \), it is found that thrust (\( T \)) and drag (\( D \)) scale as \( L^4 \). Similarly, can thus infer that the linear \( a \) and angular \( \alpha \) accelerations scale as \( L^{-1} \) and \( L^{-2} \). Experimental data supporting the above scaling law can be seen in Figure 2.

Fig. 2: The Mach number for small quadrotors scales with the square root of the characteristic length suggesting Froude scaling at these length scales. The Pelican and Hummingbird were built by Ascending Technologies[2], and the Nano and Nano Plus by KMel Robotics[3]. The PPR[1] and Pico quadrotor are experimental prototypes, while the Robobee is a flapping wing vehicle capable of insect flight[4].

Figures 3a and 3b compare the mass contributions of various physical components in COTS quadrotors and the Pico-Quadrotor as an effect of scaling down.

This section is described in detail in [5].

III. ELECTRONICS

A. Autopilot

Figure 4 shows the custom designed autopilot. It comprises of seven major components. An ARM Cortex M4 STM32F373 microprocessor, interfacing with an Atmel AT86RF212 900MHz Zigbee transceiver for wireless communication and an InvenSense MPU-6050 six axis MEMS gyro + accelerometer for inertial sensing. Four DC brushed

![Fig. 1: Our 25g Pico-Quadrotor.](image)

![Fig. 2: The Mach number for small quadrotors scales with the square root of the characteristic length suggesting Froude scaling at these length scales.](image)

![Fig. 3: Mass Distributions](image)
motor drivers drive the motors and a power management circuit regulates power for the various components on the circuit board. An integrated battery charging circuit completes the autopilot. A USB connection to the microprocessor allows for programming and as an input to charge the Li-Po battery.

Though these sub-modules collectively comprise of a sizable 72 individual electrical components, we were able to integrate them on a 30mm × 30mm PCB. We achieved this level of component density by using the smallest component packages suitable for manual soldering. For example, we used the 0402 package for resistors measuring only 1.0mm × 0.5mm, while the larger ICs have a terminal pitch of only 0.5mm.

This autopilot is made of a 1.6mm thick double layered PCB and also serves as the main structural component of the Pico-Quadrotor. The fully-populated circuit board has a footprint of less than 34 cm² including the arms for the quadrotor and weighs only 5g – almost as much as a US Quarter Dollar coin.

The Pico-Quadrotor is powered by four DC coreless motors and carries a 3.7V, 340mAh Lithium Polymer battery. The motors are easily attached to the autopilot with 3D printed motor mounts and the battery is affixed directly to the PCB with a patch of Velcro™. This autopilot is key to the agile yet stable flight of the Pico-Quadrotor as it runs the high-speed onboard attitude estimation and control. In addition to maintaining stable flight, the autopilot wirelessly transmits the measured inertial rates, calculated orientation, on-board battery voltage and commanded control inputs back to the base station, for data logging and post processing.

We have also created a software and hardware database of the various modules on the autopilot, making it easy for the designer to modify the hardware design and update corresponding software libraries. The development of this “ecosystem” is in collaboration with ModLab[6]. Owing to the modular design and rapid fabrication methods employed in our work, it takes only 40 minutes to assemble a Pico-Quadrotor including soldering the PCB, flashing the firmware and adding peripherals like motors, propellers etc.

B. Inductive Charging

To extend the effective mission life of the Pico-Quadrotors, they have an integrated a battery charger on-board. This charging circuit draws power from an inductive coil and rectifier attached to the base of the robot. This charging circuit adds 3g to the total mass of the robot.

On depleting its onboard battery, the Pico-Quadrotor can land on a charging station and recharge its battery using resonant inductive coupling.

IV. Controllers

The low level attitude control loop running onboard the robot uses acceleration and angular rate estimates from the onboard IMU to control the desired roll, pitch, and yaw and runs at approximately 800 Hz. The higher level position control running on a remote computer runs at 250Hz and uses estimates of position and velocity of the center of mass from the Vicon[7] motion capture system to control the trajectory of the quadrotor in three dimensions. These position and orientation controllers are described further in [8].

V. Conclusion

We present the design of the Pico-quadrotor weighing about 25g, capable of fully autonomous fast and agile flight and also capable of autonomous wireless battery recharging. In addition to carrying the battery, it can also carry a small wireless camera to transmit images to the base station. We also demonstrate the robustness of our framework in indoor autonomous flight experiments involving traversal at speeds of up to 6 m/s. The design files and related software under will be made open source by the end of this year.

REFERENCES