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Design Principles of Large Quadrotors for Practical Applications

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***Abstract*— Virtually all quadrotors used in research weigh less than 2 kg, and carry payload measured in hundreds of grams. To be useful platforms for expanded operations, these vehicles must be capable of carrying greater weight. Several obstacles in aerodynamics, design and control must be overcome to enable the construction of larger craft with payloads in excess of 1 kg. We report the key design considerations essential for the construction of heavy quadrotor MAVs and demonstrate a 4 kg quadrotor with 1 kg payload.**

I. INTRODUCTION

Quadrotor Micro Air Vehicles (MAVs) have been the subject of significant study since gaining the attention of robotics researchers in the early 2000s. These efforts have primarily focussed on the attitude control aspect of quadrotors, and numerous papers have been written concerning their dynamics and describing methods to regulate their flight. Most groups have modified commercially available off-the-shell quadrotors with custom avionics. Virtually all quadrotors in use around the world have been based on hobbyist equipment.

Quadrotors are attractive for use in industry due to their inherent robustness and compact layout, but there have been few inroads into the development of larger quadrotor MAVs scaled for industrial use. We identify 1 kg as a benchmark payload for useful missions.

Previous attempts to construct large, heavy quadrotors (>2 kg or >1 m), such as the Hoverbot [1] and Cornell Autonomous Flying Vehicle 'AFV', were partial successes [8]. The 6 kg Hoverbot was built from four hobby helicopters joined at the tail. It could lift itself into the air, but never flew off its sensored test gimbal. The 6.2 kg AFV was custom-built with hobby propellers, motors, electronic speed controllers and lithium batteries. It used shaft encoders for closed-loop rotor speed control, and Kalman filters to perform inertial sensor bias estimation. It flew with tethered power but flight damage prevented further testing.

In the commercial sphere, several groups announced plans to market 4-6 kg devices, but these did not manifest in products, whereas numerous examples of sub-2 kg craft are now readily available. The paucity of heavy quadrotor MAVs can be attributed to the numerous design challenges encountered as the weight of the vehicle increases, and to the attendant engineering rigour that must be exercised to safeguard expensive hardware.

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Fig. 1. The X-4 Flyer in Flight.

Over the past five years, we have developed a heavy quadrotor, conceived as a precursor to practical industrial quadrotor MAVs. The Australian National University's (ANU) X-4 Flyer Mark III is a 4 kg vehicle with a 1 kg payload (see Fig. 1). It is built from custom avionics, rotors fabricated in-house, hobby brushless motors and lithium polymer batteries.

In this paper we report the critical design aspects of heavy quadrotors: rotors, motor speed controllers and attitude dynamic control. We then describe the systems and design of the X-4 hardware to satisfy these aspects and report the performance realised in indoor and outdoor flight tests. We provide a short set of design guidelines for large quadrotors. Our findings are summarised with a brief conclusion.

II. ROTOR DESIGN

Efficient, compact, high-lift rotors are essential for useful flight time and payload. Previous efforts to design rotors or drive systems have mostly consisted of a try-and-see approach, combining off-the-shelf parts [2] [8], but for best performance rotors must be tuned to the specific needs of the aircraft. We previously described a method to design a complete drive system suitable for large quadrotors [9] [12]. In this section we review the essential facets of rotor design that apply to all quadrotors and, in particular, larger vehicles.

A. Rotor Size, Speed and Power

The power required for flight is inversely proportional to the radius of the rotor [13]. The rotor radius should be maximised to reduce power for given thrust within the limit of the size of the vehicle, weight of the rotors and the scale of the environment in which the MAV is to operate. Heavy quadrotors intended to operate in human-scale environments compound the problem — their rotors may not be substantially larger than that of smaller quadrotors, due to space

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constraints, but they may be required to develop significantly greater thrust. The X-4 Flyer, for example, weighs ten times as much as the RC Toys Draganflyer V, but has only 20 per cent more rotor area [12].

These relatively small rotors must correspondingly rotate very fast, compared with a conventional helicopter, to generate sufficient thrust [13]. The thrust produced by a rotor is proportional to the fourth power of its radius and the square of its angular velocity. To decrease rotors radius, tip speed must be increased quadratically. The effective limitations on rotor speed are the motor drive torque and compressibility of air at the blade tip. Mach 0.4 is considered to be a practical compressibility bound [7].

Additionally, the very high speeds of a small rotor make them potentially dangerous to work around. Given two identical rotors producing the same thrust, one half the size but four times the speed, the smaller rotor will contain twice the rotational energy of the larger one. While most smaller quadrotors do not pose great danger — their small fragile blades break easily on contact — the safety of larger quadrotors must be accorded due consideration when selecting rotor speed.

B. Response Time

The swashplates of conventional helicopters allow instantaneous thrust changes, whereas most quadrotors use fixed-pitch rotors and must therefore accelerate and decelerate their rotors to effect pose changes. As rotor size increases, mass and rotational inertia also increase. The rotor drive system must be capable of developing sufficient torque to produce the required acceleration. It is desirable to make the rotor and mast as light as possible to increase actuator bandwidth.

In the case of the X-4 Flyer, it was found that a natural motor-rotor rise-time of 0.2 seconds made the vehicle uncontrollable. Feedback control was required to improve the actuator bandwidth.

Especially large quadrotors may use collective variable blade pitch on each rotor and avoid the motor dynamics problem entirely. This was the approach taken by the Hoverbot [1]. The authors are not aware of any MAVs of this sort that have been flown, but it is expected that this is a viable alternative. However, collective blade control comes at the cost of increased mechanical complexity, which mitigates the robustness advantage of quadrotors.

C. Airfoil and Blade Design

Common practice for small quadrotors designers is to coopt commercial quadrotors rotors or hobby airscrews. However, these are not suitable for large quadrotors due to their flimsy construction, weight, high pitch angle or airfoil inappropriate to the required flight regime. Efficient small-scale fixed-pitch rotors optimised for large quadrotors are not generally available off-the-shelf.

Quadrotors rotor blades operate in high-viscosity laminar flow regimes due to their low Reynold's numbers, in the order of 100,000. For these conditions, high aspect-ratio airfoil sections such as the ANUX2 [9], DFmod3, VR8 and MA409sm are most appropriate. The airfoil should have low camber, a thin cross-section to reduce profile drag, and sharp trailing edges to reduce separation drag.

Unfortunately, such thin airfoils induce significant aerodynamic moments that can dominate the torsional rigidity of the blade in the case of heavy quadrotors. Aerodynamic performance must be compromised to prevent the blades from twisting into stall under load. By shifting the airfoil's centre of thickness and camber away from the leading edge, the centre of pressure is moved rearward and the magnitude of the pitching moment is reduced. A more rounded leading edge reduces the sudden onset of stall, and a proportionally thicker body and more mass towards the leading and trailing edges can stiffen the section. The ANUX2 section used on the X-4 was specifically designed for the flyer's flight regime and resistance to twist.

The ideal flow regime is maintained across a blade with hyperbolic twist and taper — the theoretically optimal shape for hover [13, p 46]. However, even particularly rigid blade sections will deform slightly in flight. It is possible to predict this physical distortion and compensate with initially decreased angle so that the blade will twist up into the correct angle of attack under load. We use the term 'pretwist' to describe this modification to the ideal profile. A method for calculating pretwist and simulating blade performance has been reported previously [9].

III. Drive Systems

Motor dynamic performance and robustness are crucial to quadrotor performance and reliability. Small quadrotors, such as the Draganflyer V, typically employ of power FETs modulating drive voltage to DC motors. Larger craft employ brushless motors with Electronic Speed Controllers (ESC). Properly engineered ESCs are required to extract maximum performance. In this section we describe the hardware and control aspects of drive system design essential to large quadrotors.

A. Electronic Speed Control Hardware

Common practice in the past has been to use off-the-shelf hobby aircraft ESCs because they are readily available and light weight. However, these have several drawbacks.

Most importantly for quadrotors, hobby controllers have a built-in slew-limit designed to reduce the in-rush current draw upon step speed changes. Without it, in cases where the ESC is powered from the motor power supply, the in-rush current and internal resistance of the batteries can cause the power bus voltage to drop until the microcontroller's regulated supply fails and the controller resets. In the case of the X-4 Flyer, slew-limited hobby speed controllers could not respond fast enough to stabilise the craft.

Generally, hobby ESC microcontroller code and internals are inaccessible. High-gain, closed-loop speed control around the 50 Hz update rate of hobby RC equipment is impractical. Also, no measurement of the rotor speed is accessible externally so resolvers, or back-emf or Hall-effect sensors must be added.

It awaits to be seen if programmable hobby ESCs now becoming available, which can be hooked up to PCs for fine-tuning, can be adapted for large quadrotor speed control. In the near term, a heavy quadrotor will almost certainly require custom drive electronics. Commercial quadrotor developers, such Acceleronics, already use custom control electronics to drive their motors.

An additional problem quadrotors face is that the surge current due to step torque change can be very large - spikes as high as 100 A have been measured in the X-4's drive [11]. Without sufficiently robust MOSFETs, these spikes can damage the ESC switching circuits and lead to premature failure of the board. To avoid these problems, ESCs ramp speed changes slowly, limiting the bandwidth of the actuator.

B. Dynamic Compensation

Quadrotors must have fast thrust dynamics - the motors must accelerate the rotors quickly to allow authorative attitude stabilisation. Most current quadrotors have light rotors that allow for fast speed changes without additional control. Large quadrotors must have low-drag rotors with high inertia and need local control to artificially improve the motor response. In practice, the closed-loop performance is heavily constrained by limits on the available instantaneous current draw on the batteries and this dominates the control design.

Brushless motors are a single pole dynamic system, and proportional feedback control is suitable. The maximum gain than can be realised by the torque-limited plant is bound by the maximum slew-rate that disturbance noise and sinusoidal references may demand without inducing rate saturation. We have previously described a method for calculating an optimised controller for a slew-saturated drive [11].

Precise reference tracking of the plant is not the foremost task of the controller. The motor-rotor subsystem can be designed to be type 0; that is, no pure integral term in the controller. The attitude control system for a full MAV will contain integral terms that will compensate motor set-points to ensure flight stability of the vehicle.

IV. Attitude Stabilisation

Attitude control is central to quadrotor design. Large quadrotors pose additional challenges due to the need to consider more completely the dynamics expressed by rotorcraft and the challenge of parameterising and testing controllers prior to flight. In this section we discuss the implications of large quadrotor dynamics and principal considerations for attitude controller design and testing.

A. Dynamic Modelling

Mathematical dynamic models of flight behaviour are essential for good control design and analysis. A common model used to represent quadrotor behaviour is that of Hamel *et al* [6]. The most basic quadrotor model used consists only of rigid body dynamics with abstract force and torque actuators and no aerodynamics. The quadrotor is commonly represented as a rigid body mass with inertia and autogyroscopics, acted upon by gravity and control torques.

Simple quadrotor dynamic models are not capable of representing the complex helicopter behaviour exhibited by large quadrotors. In particular, they omit the blade flapping effect which is critical to understanding oscillatory helicopter modes. Additional effects unique to quadrotors include rotor flapping due to yaw and variable rotor inflow velocities as a result of craft pitch and roll. We combined these aerodynamic effects with the basic equations to produce a more detailed model in previous work [10]. Linearised differential equations for the flyer are:

$$m\ddot{x} = -mga_{1_s} - mg\theta \tag{1}$$

$$\mathrm{I}_{YY}\ddot{\theta} = 4dC_{\mathrm{T}}\rho AR^2\omega_0\delta\omega + mga_{1_s}h - \frac{a}{2}\sigma\rho AR\omega_0 d^2\dot{\theta} \tag{2}$$

where m is the mass, g is gravity, a_{1_s} is the longitudinal flapping angle, θ is the pitch angle, I_{YY} is pitch rotational inertia, d is rotor offset from the CoG, C_{T} is the rotor non-dimensionalised thrust coefficient, ρ is air density, A is rotor area, R is rotor radius, ω_0 is rotor angular velocity, h is the height of the rotors above the CoG, a is the airfoil polar lift slope, and σ is the rotor solidity.

Flapping dynamics are beginning to be recognised as important aspects of quadrotor dynamics; even very small quadrotors exhibit flapping. As shown by Prouty, the dominant dynamics of a rotorcraft are associated with the longitudinal flapping dynamics of the vehicle [13]. The nature of the instability of quadrotor dynamics was shown to be dependent upon the height of the rotor above the centre of mass. As was shown using the Bode Integral, setting the rotors to be on, or just above, the plane of the centre of gravity maximises controllability [10]. In the case of large quadrotors with limited actuator bandwidth this may be a crucial design point.

B. Dynamic Controllers

Quadrotor attitude control has been well researched by groups at many universities. A variety of control techniques have been implemented successfully on quadrotor MAVs — PID, LQ [3], feedback linearisation, nonlinear PD and PD^2 [2], backstepping [5], adaptive nonlinear control, sliding-mode [15] and robust control.

In practice, the performance of simple control schemes are competitive with even very complex schemes. The dynamic regulation performance of most controllers is within $\pm$ 2 degrees of level tracking, and the best in the range of $\pm$ 0.5 to 1 degree. It is the authors' assertion that the limiting factor in quadrotor dynamic control is the performance of the actuators. Less complicated designs may, in fact, have an advantage inherent to their simplicity — Bouabdallah *et al* found that PID performed better than other controllers due to the simpler method's tolerance for model uncertainty [3].

C. Parameterisation and Uncertainty

Robustness to uncertainty is desirable for large quadrotors where the craft may comprise a substantial investment in time and money. Unlike small, easily replaced craft, large

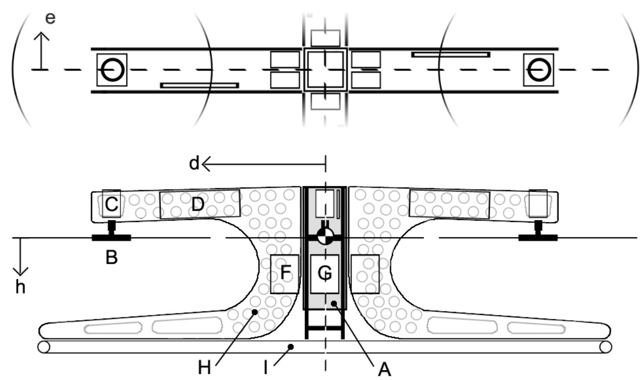

Fig. 2. X-4 Component Offsets.

	Part	mass/kg	d/m	e/m	h/m
A	Avionics	0.242	0	0	-0.02
B	Rotor	0.046	0.315	0	0
C	Motor	0.288	0.315	0	-0.06
D	ESC	0.074	0.15	0.035	-0.055
E	Powerbus	0.099	0	0	-0.13
F	$\mathrm{Batt}_{\mathrm{long}}$	0.165	0.0125	0.06	0.035
G	$\mathrm{Batt}_{\mathrm{lat}}$	0.165	0.0	0.04	0.035
H	Arm	0.039	0.157	0.035	0.04
I	Hoop	0.200	0	0	-0.17
	Centre frame	0.600	0	0	0
	Fasteners	Rem.			

TABLE I

COMPONENT MASSES AND OFFSETS.

quadrotors cannot allow for try-and-see dynamic stability testing; instability in flight caused by an erroneous control law or poor parameterisation of the model is liable to severely damage or destroy the craft.

Given the unstable attitude dynamics of quadrotors, it is not possible to perform classic step response experiments to characterise the vehicle prior to developing at least a basic attitude controller. This problem is compounded by the difficulty in parameterising heavy, fragile vehicles where it is not be feasible to directly measure parameters such as the rotational inertia. The intermediate step is to mount the vehicle on a gimbal for parameterisation and testing. This does not provide data on translational dynamic phenomena, but provides a first-cut for proving the function of flight regulators and performing characterisation experiments.

V. THE X-4: A LARGE QUADROTOR MAV

The X-4 Flyer consists of a chassis, rotors, motors, power cells and avionics. Each subsystem is listed in the weight-budget, Table I, and described below. Component distances are measured with respect to the rotor plane, (masses ± 0.005 kg, distances ± 0.005 m) (see Fig. 2).

A. Chassis

The X-4 has an aluminium centre frame with carbon fibre-foam sandwich arms. Motors and batteries are mounted as far from the central axis as possible to slow the pitch and roll dynamics. The arms angle down slightly to provide more clearance between the bottom of the arms and flapping rotor tips. The rotor mounts are teetering hubs, a freely pivoting joint between the drive shafts and rotor blades.

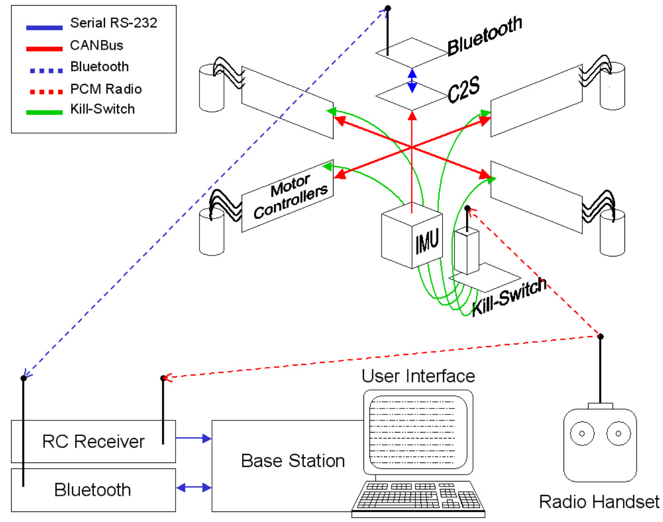

Fig. 3. Avionics Communications Structure and Subsystems.

Avionics and sensors are mounted in a vibration-isolated pod housed inside the centre frame and each motor is mounted on rubber-isolated brackets. Both isolation systems are tuned to damp the frequency of the rotors.

B. Drive System

The X-4's rotors are designed to lift the flyer with an additional 30 per cent control margin (greater than 5.2 kg). The blades are three-ply carbon fibre and were designed and fabricated at the ANU.

The rotors are driven by Jeti Phasor 30-3 brushless motors for radio-controlled aircraft. They offer high torque performance that allows for direct drive of the rotors, eliminating the need for gearing. The motors can develop more than 300 W and are rated up to 35 A.

Custom motor control boards commutate the motors. These were developed by the CSIRO Queensland Centre for Advanced Technology ICT group. The boards use the Freescale HC12D60A microprocessor and Toshiba TB9060 brushless motor speed control chip. Unfortunately, we did not anticipate the in-rush current problem and consequently had to implement a slew saturation and employ a control scheme to maximise dynamic response around it [11].

Power is provided by 24 Li-Poly 2000 mA·h high-discharge cells. Each cell has a nominal voltage of 3.7 V, ranging from 4.2 V fully charged and dropping to 3 V at depletion. Each cell can deliver up to 20 A. The batteries are connected to a power bus of six parallel sets of four cells in series; that is, 14.8 V nominal voltage and 30 A of current draw per motor. This gives the flyer an expected flight time of 11 minutes at hover speed.

C. Avionics

The avionics systems communicate over a CANbus network (see Fig. 3). A CSIRO Eimu IMU provides angular rate and acceleration measurements and angular position

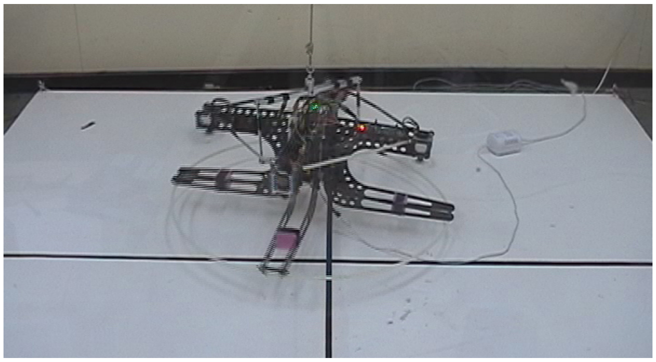

Fig. 4. X-4 Flight in Ground Effect.

estimates at 50 Hz. The motor control boards implement a distributed PID controller; each controller receives the same broadcast IMU data and calculates the control action appropriate to its motor. A CANbus-to-Serial converter board translates network traffic into serial data for transmission.

Directions to the robot and information about the X-4's state are transmitted over a long-range Bluetooth serial module connected to a base station PC running Linux. The Bluetooth unit has a range of up to 100 m. Telemetry from the flyer is logged by the base station and displayed on-screen. The user can issue commands via the PC keyboard or a JR-X3810 radio handset.

The radio handset can also trigger a safety kill-switch on the X-4, independently of the Bluetooth communications channel, using an onboard radio receiver. In an emergency, the kill-switch can stop the rotors instantly by disabling the motor control boards, even if data communications is lost.

VI. Flight Performance

The X-4 underwent extensive testing prior to free flight outdoors. With the exception of the outdoor flight, all tests were performed in a test cage in the ANU Mechatronics Laboratory. Initial tests on a gimbal to validate the attitude controller were reported previously [10].

The simplified plant and controller transfer functions are:

$$\mathrm{G} = \frac{1.4343\times10^{-5}(z-0.9916)(z+1)(z-0.9997)}{(z-0.2082)(z-0.9914)(z-1.038)(z^2-1.943z+0.9448)} \quad (3)$$

$$\mathrm{C} = 400\left(1 + 0.2\frac{0.02}{(z-1)} + 0.3\frac{(z-1)}{0.02}\right) \quad (4)$$

For testing with translational freedom the aircraft was suspended just above the ground at start-up. The rotors were held at idle when attitude controller was turned on, and then brought up to flight speed to carry the weight of the flyer (see Fig. 4). In this test the attitude control integral was not enabled, causing the flyer to stabilise at non-zero angles and drift across the test area. The X-4 flew at a height of approximately 0.4 m in ground effect and regulated its attitude within ±1 degree of equilibrium (see Fig. 5).

For testing beyond ground effect the X-4 was flown tethered indoors. After engaging the attitude controller the suspended flyer was hoisted up 1.5 m into the air before bringing the rotors to flight speed. A pilot sent attitude

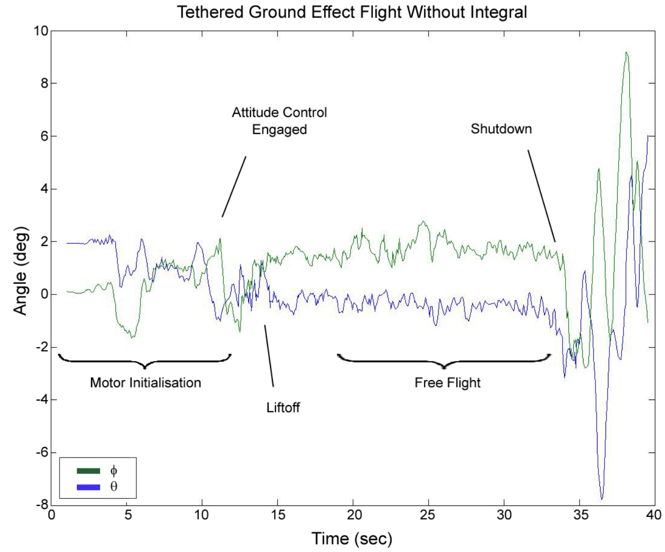

Fig. 5. Autonomous Pitch and Roll Angle Stabilisation in Ground Effect.

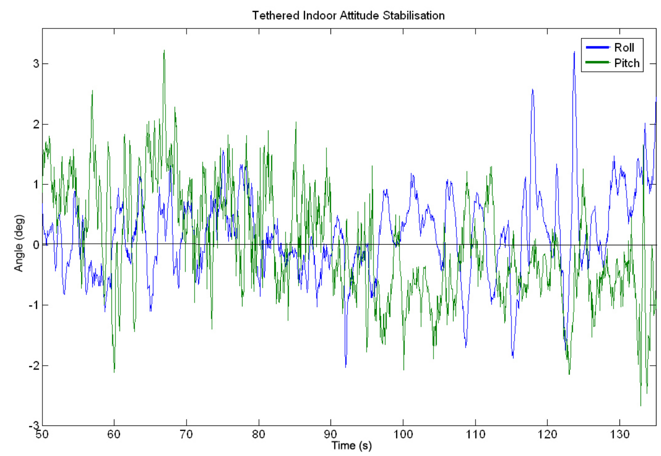

Fig. 6. Tethered Indoor Autonomous Pitch and Roll Angle Stabilisation.

reference commands to the flyer to keep it centered in the test area; the pilot did not stabilise the vehicle. The X-4 flew at a height of approximately 2 m and regulated its attitude within ±2 degrees of level (see Fig. 6).

The outdoor test took place on an ANU oval. A smooth platform was used for take-off to allow the flyer to slide sideways freely rather than catch and flip. To avoid integrator wind-up, the X-4 was brought up to flight speed quickly, then hopped into the air under manual mode before switching to autonomous control. During the flight a pilot sent commands to the flyer to control throttle and keep it within the cordoned test area; the pilot did not stabilise the vehicle. The X-4 took off from the ground and flew to above 2 m and stayed airborne for 25 seconds (see Fig. 1). For ten seconds of the flight, the pilot made no stick corrections; the flyer regulated its attitude within ±1 degrees of level (see Fig. 7).

VII. General Quadrotor Design Guidelines

In developing the X-4 Flyer, our experience has identified several rules of thumb for designing quadrotors. The follow-

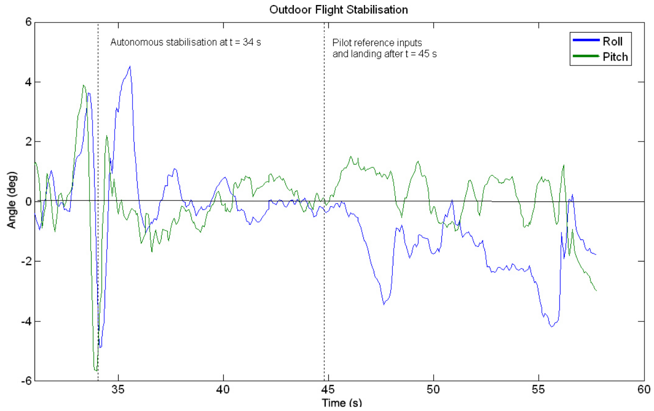

Fig. 7. Outdoor Flight Autonomous Pitch and Roll Angle Stabilisation.

ing recommendations are for large quadrotors for indoor use, but can be applied to a variety of quadrotors and missions.

- Safety is important. High-energy quadrotors designed to operate indoors or around humans must be equipped with suitable measures to ensure safety. Consider strong ducts to shield rotors and redundant kill-switches.
- Maximise rotor size. This reduces power draw and rotor speed and improves safety. Larger rotors also slow the attitude dynamics and increase damping.
- Use suitable rotors. Employ light-weight low-pitch blades designed for the static thrust. Thin airfoils distort in flight and must be thickened or given pretwist. Consider making both blades a one-piece moulding to simplify manufacture and balancing.
- Use suitable electronic speed controllers. Use hardware that gives you access to the microprocessor and speed sensors. Avoid slew-saturation and provide the microprocessor with power separate from the motor cells. Use over-rated MOSFETS or protect against surges. Most hardware failures experienced by the X-4 were due to a MOSFET failing on start-up.
- Use motor control to improve rotor dynamic response.
- Minimise avionics complexity. Communications, electronics and code robustness are difficult to guarantee as bugs can go unnoticed until disaster occurs. If possible, integrate actuator, control and sensor processing tasks into a single microprocessor to reduce communications overheads, latency and code.
- Maximise mechanical robustness. The principal advantage of quadrotors is their few moving parts - exploit this by reducing the design complexity of the rotor head and chassis. Use few fasteners in these components to reduce vibration loosening and weight. Consider making these one-piece items.
- Plan for vibration. Integrate isolation systems into the motor mounts. Quadrotor motors weigh much more than avionics and are easier to damp. It is much easier to build isolation into a design than to retrofit it later.
- Maximise control robustness. Control that is robust to parameterisation error is essential for vehicles which must work first time. Use incremental steps to validate flight control before attempting free flight.

VIII. CONCLUSIONS

The construction of larger quadrotor MAVs is necessary to translate current quadrotor research into useful industrial vehicles. The key challenges to be overcome were efficient aeroelastic rotor design, fast motor-rotor dynamic response and robust attitude stabilisation. These were overcome through the use of custom designed hardware, consideration of vehicle dynamics and insight into the uniques aspects of heavy quadrotor design.

We have demonstrated a 4 kg quadrotor with a 1 kg payload, capable of stabilising itself in outdoors flight with $\pm$ 1 degree of level precision. To our knowledge this is the first successful outdoor test of a $>$4 kg quadrotor MAV.

IX. ACKNOWLEDGMENTS

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