Modelling the Lama Coaxial Helicopter

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Abstract

Control of a helicopter is complex, and includes cross coupling of forces and balancing of forces. While sophisticated and advanced controllers can achieve stable control, good mechanical design can reduce the problems and hence make tuning the control loops easier. In this paper, we argue that a coaxial-rotor design solves a number of problems that make control of a four-rotor helicopter difficult. First, we examine several coaxial helicopters and discuss the concepts behind coaxial propulsion. Then we develop a dynamic model of the Lama coaxial helicopter. Finally, we compare this model to a model of the Dragonflyer four-rotor helicopter to show the difference in dynamics and how they impact the control.

1 Introduction

A number of research groups are investigating the topic of indoor aerial robotics. Different groups are undertaking this research for different purposes. Some are trying to understand the aerodynamics of flying robots, while some are building a platform for testing control algorithms. What we are trying to do with indoor aerial robot is to develop a sensing platform for site assessment in urban search and rescue.

1.1 Site Assessment Task

A disaster is a natural or man-made event that negatively affects life, property, livelihood or industry, often resulting in permanent changes to human societies, ecosystems and environment. Huge disasters in history caused up to millions of casualties [Wikipedia, 2007] and disasters are destroying building and killing people right now [Havaria Information Service, 2007].

Most disasters that cause large number of casualties happened in metropolitan areas, thus rescuers may need to enter collapsed buildings to save survivors. Previous research [Greer *et al.*, 2002] on urban disaster rescue identified the importance of site assessment. Site assessment provides the information necessary for rescuers to accomplish a mission, such as possible location of survivors and their condition, and dangerous situations that might threaten rescuers' lives. Rescue teams cannot safely enter the disaster site until they acquire sufficient information by site assessment.

Since collapsed buildings are highly unstable, a manned helicopter cannot fly close to disaster site because the vibration of helicopter blades may cause further slippage. As a result, site assessment can only be performed with the limited information that rescuers can gather from the boundary of the site. Therefore, site assessment takes time. In the Thredbo landslide in 1997, police contained the site 1 hour after the accident happened. But it took a further 5.5 hours to finish the assessment and allow rescuers to enter the site [Hand, 2000].

With technology advancing, ground robots have started to be used in rescue missions. However, ground robots are slow and their ability to cross rough terrain, such as big slopes or streams, is limited. Hence, the ideal tool for site assessment is a flying robot that can fly into dangerous site, perch and gather information. This robot must have the ability to fly indoors to detect survivors under collapsed buildings.

To achieve indoor flight, the flying robot needs to negotiate narrow corridors and with all kinds of obstacles, as well as provide useful information to human rescuers. Therefore, this robot needs to be able to fly in six degree of freedom with minimum meandering and be equipped with sensors to know its own states and detect the environment. This robot must be easily to control and perform a certain level of autonomous flight because it is most likely to be controlled by untrained personnel.

1.2 Indoor Aerial Robots

Because an indoor aerial robot needs to fly in a very complicated environment, the stable flight constraints for them is much more restricted than outdoor flying robots.

There are several kinds of aircraft structures that have been used in indoor flight by robotic researchers. The most common types are airships, ultra-light fixed-wing planes, flapping-wing aircrafts, single-rotor helicopters and four-rotor helicopters.

Airships [Iida, 2001] are easy to fly by using helium to produce lift against gravity. There is no need to generate an external lift force. They can move with several DC motors and suffer minimal damage when they hit obstacles, with proper protection. The aerodynamics of airship is relatively simple compared to other structures, so it is easy to model. However, an airship has limited moving freedom and needs helium to fly.

Ultra-light fixed-wing planes [Nicoud and Zufferey, 2002; Green and Oh, 2003] are constructed with lightweight material and fly very slowly indoors. This structure is easily to control, but it cannot hover and requires space to make a turn. Nicoud and Zufferey designed a model plane, which can navigate in a 10*10 m room with a speed of 1.4 meter per second. Green and Oh's design also needed the same size of room to fly freely.

Flapping-wing aircraft [Deng *et al.*, 2003] simulate the flight behaviours of a hummingbird or an insect. Although sustained flight has been demonstrated with Linear-Quadratic Regulator (LQR) controller, full motion control with payload in an indoor environment has not been achieved. The main drawbacks of this design are limited payload and complex nonlinear dynamics.

Conventional single-rotor helicopters [Amidi *et al.*, 1999; Sanchez *et al.*, 2007] use a main rotor to generate lift and a tail rotor to balance the torque caused by main rotor rotation. Motions of a single-rotor helicopter are mainly controlled by a swash plate that links to the main rotor. The swash plate changes the collective pitch and cyclic pitch of the main rotor through servos, to enable helicopter to move in six degree of freedom. This structure causes strong cross coupling between control inputs. Thus, control of single-rotor helicopter is difficult due to its coupled dynamics. Furthermore, exposed tail rotor blades have a high possibility to collide with something in an indoor environment. A detailed theoretical comparison between single-rotor helicopters and coaxial helicopters will be covered in Section 2.

Four-rotor helicopters [Pounds *et al.*, 2002; McKerrow, 2004] use four rotors to achieve stable hovering and flight. The rotors can be enclosed to avoid collision and the mass can be distributed from the centre to make the helicopter easier to control. The four rotors have fixed pitch and no servo is connected to rotors. Hence, helicopter movements are controlled by difference of four forces generated by changing the rpm of the rotors. Further analysis of four-rotor helicopter and a comparison to coaxial helicopter will be covered in Section 4.

There are also coaxial helicopters [Nardi and Holland, 2006; Rezgui *et al.*, 2006] that use two rotors that rotate in opposed direction to cancel the torque. Compared to a single-rotor helicopter, coaxial design has more a compact structure without tail rotor and can provide stronger thrust with two main rotors. Main rotor blade collision can be avoided with a protection frame that surrounds the helicopter. Also, coaxial helicopters share a lot of aerodynamic features with single-rotor helicopter, thus the aerodynamics and modelling theories for coaxial helicopters are much more sophisticated than for other novel designs. The only disadvantage of the coaxial helicopter is the increased mechanical complexity. The rotor hub needs to be carefully designed to drive two conter rotating rotors. We can slove this problem by purchasing a commercial product instead of creating our own.

In order to investigate the flying features of coaxial helicopters and develop a model that can be used for research, we bought a Lama X.R.B from Hirobo Model Enterprise Company [Hirobo, 2007]. The Lama X.R.B is a radio-controlled coaxial helicopter and an ideal tool for understanding the coaxial configuration.

In this paper, we will first introduce the coaxial design concept by illustrating several coaxial helicopters. Also, comparison to single-rotor helicopter will be made to show the advantages of coaxial design. And then we will discuss the design of Lama and construct a dynamic model of Lama for control purposes. To show the advantage of a coaxial structure, a comparison between four-rotor helicopter Dragonflyer and coaxial helicopter Lama will be given in Section 4. At last, we will conclude this paper by pointing out our future works.

Figure 1 Lama X.R.B.

2 Coaxial Concepts

Although most helicopters employ a conventional single-rotor configuration, pioneers of helicopter building knew about the fundamental advantages of coaxial design. Back in 1754, Mikahail Lomonosov from Czarist Russia had already proposed a coaxial rotor machine to elevate meteorological instruments using a wound-up spring device. This machine was modelled after the famous Chinese toys that consisted of propellers at the end of a stick and fly into air by being rapidly spun between human hands. In 1928, D'Ascanio from Italy constructed a helicopter with two sets of coaxial rotors and reached a major altitude of 18 meters. There were also other projects attempting to build a coaxial helicopter in early days of helicopter development [Heatley, 1985].

2.1 Coaxial benefits

The main reason that makes a coaxial helicopter so special is because it uses two contra-rotating rotors to compensate each other's torque that they apply to the helicopter fuselage when they rotate. Without a tail rotor, coaxial helicopter can devote all the power in developing lift, which increases the power efficiency of a coaxial helicopter. Experimental data shows that the coaxial design requires 5% less power in hover for same given thrust as single-rotor helicopter [Coleman, 1997].

Also, the coaxial configuration has a more compact structure than a single-rotor because it does not need to mount a rear shaft longer than the main rotor's blade-swept radius in the airframe. The result of this is a reducing of coaxial-rotor helicopter size by 35-40% as compared with the single-rotor one. In this instance, the moment of inertia of coaxial helicopter decreases, which increases the controllability and manoeuvrability of the helicopter [Petrosyan, 2007].

These benefits of coaxial helicopters result in two series of legendary coaxial helicopters: Ka-25 series and Ka-50 series from the Kamov Company. The Ka-25 series are mainly used for transport, which take advantage of coaxial design's high power efficiency and high payload. The Ka-50 series are attack helicopters. They have small vulnerable area and fast yaw angle speed in hover owing to coaxial design, which increases their survivability in combat.

A fundamental disadvantage of a single-rotor helicopter is its dissymmetry of lift in forward flight. In forward flight, the advancing rotor blades travel through the air quicker than the retreating blade (the speed difference is twice the helicopter forward speed), which means that airflow over advancing rotor could be supersonic while the retreating side could enter the stall condition and barely generate lift. Therefore, Dissymmetry of lift results in an upper speed limit for single-rotor helicopter in forward flight.

Coaxial helicopter solve this problem because any time on either side of the rotor disk, there are an advancing blade and a retreating blade, thus the lift difference will be cancelled, at least theoretically. Sikorsky Company produced the XH-59A to test this Advancing Blade Concept in 1972. As development went on, the XH-59A was able to reach and maintain speeds in exceeds of 515 kilometres per hour in level flight in 1978 [Ruddell, 1981].

2.2 Coaxial Unmanned Aerial Vehicle

Unmanned coaxial helicopters were developed half century ago. Back in 1946, Gyrodyne Company developed the QH-50 series for the United State Navy for anti-submarine missions. The QH-50 can carry torpedoes and was guided remotely by a human pilot to the target using the ship's radar system. Also, the Kamov produced Ka-137 coaxial robot helicopter. The Ka-137 is equipped with artificial intelligence based automatic control system. The onboard inertial and satellite navigation system ensures automatic flight in a complicated outdoor environment.

Airscooter, the company that released the first personal coaxial helicopter, also designed a series of coaxial Unmanned Aerial Vehicles (UAV). Their series use both petrol engine and electric motor. The petrol engine UAV can achieve maximum of 80 kilometres per hour in forward flight with more than 4.5 kg of payload [Airscooter, 2007].

3 Lama

Lama is a radio-controlled coaxial toy-helicopter. A human pilot controls the helicopter via a radio transmitter. The transmitter has four channels, which are joystick controls for throttle, roll, pitch and yaw of the helicopter. Throttle controls the helicopter's vertical movement; yaw controls the helicopter's heading; pitch controls the helicopter's forward movement and roll controls the helicopter's sideways movement.

3.1 Design of Lama

In the of-the-shelf design of Lama, after receiving joystick commands from a human, the transmitter transmits these commands to the helicopter's embedded electronic circuit through a radio link. The electronic circuit then translates these commands to servo inputs and motor inputs to generate cyclic pitch, collective pitch, and rotor speed. These controls cause forces and torques to be applied to the helicopter and result in helicopter movement. There is also a yaw gyro embedded in the helicopter to provide feedback to the electronic circuit for stabilizing the yaw movement of the helicopter.
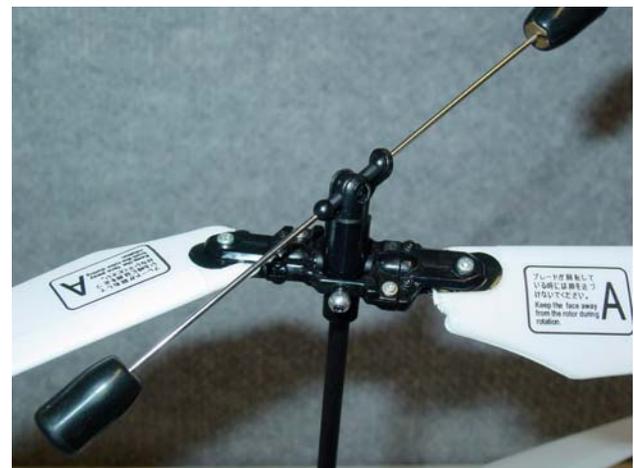

Figure 2 Blade assembly of top rotor

The two rotors are the most important mechanisms in this helicopter because they generate most of the forces and torques applied to helicopter body. The top rotor of the helicopter is not linked to any servo (Figure 2), so a mechanical stabilizer is used to induce cyclic pitch control of the rotor when it senses the inclination of the fuselage. The bottom rotor is controlled by two servos, which link to the rotor by a swash plate (Figure 3). Therefore, we cam control the cyclic pitch of the bottom rotor directly. The left and right servos control the lateral and longitudinal cyclic pitch of the bottom rotor respectively. The rotational velocity of rotors is controlled by two different motors. The front motor changes blade speed of the top rotor, while the back motor controls the bottom rotor.

Figure 3 Sliding swash plate and blade assembly of bottom rotor

Both rotors cannot change their collective pitch, so the relative pitch between two blades is fixed. For a given rotor, when the pitch of one blade increases the pitch of the other blade decreases maintaining a constant average pitch. Therefore, height control can only be achieved by changing the rotational velocity of both rotors.

Lateral pitch of the bottom rotor results in the roll of the helicopter and body movement along the y axis, while the longitudinal pitch of the rotor causes the pitch of the helicopter and body movement along the x axis. Yaw of the helicopter is produced by the rotational velocity difference between the two rotors. Changing the rotational velocity of two rotors simultaneously achieve the vertical movement of the body along the z axis.

Lama is designed specifically for indoor flight. Therefore, it sacrifices characteristics that are not required in indoor flight such as high-speed flight and fast response to achieve stable hovering and accurate movement, which increases its safety during flight. This sacrifice resulted in several mechanical design decisions.

First, it uses a stabilizer on the top rotor, which slows the top rotor's response to rapid changes in cyclic pitch of the bottom rotor by automatically controlling the cyclic pitch of the top rotor in an attempt to hold it in its current plane of rotation.

Second, cyclic pitch of the bottom rotor is controlled by a sliding swash plate, rather than a conversional ball bearing swash plate. This design reduces the overall height of rotor shaft, which reduces the torque the rotors generate around the centre of gravity.

Third, there is no collective pitch control in Lama, so it does not need a swash plate for the top rotor and simplify the control of the bottom rotor. As a result, lift can only be controlled by changing rotational velocity. This results a slower response when changing lift.

These three design features decrease the manoeuvrability of Lama but increase its stability and hence make it easier to fly.

3.2   Modelling of Lama

Before we continue our analysis of Lama, we need to construct a robot frame R and a world frame W to better illustrate the modelling of Lama. These two frames are both right-hand frames. The robot frame is fixed to the helicopter at the centre of gravity and moves with the helicopter relative to the world frame. And the world frame is fixed to the original location of the robot frame. All equations will be expressed in the robot frame. When equations need to be expressed in the world frame, they will be transformed by a transformation matrix (Equation 1).

$$^{W}T_{R} = Rot(z,\phi)Rot(y,\theta)Rot(x,\psi)Trans(d_{x},d_{y},d_{z}) \quad (1)$$

where (ψ,θ,ϕ) is the yaw, pitch and roll angles respectively and (d_{x},d_{y},d_{z}) is the distance between helicopter centre of gravity and original location of the helicopter. And the rotation matrix is

$$^{W}Rot_{R} = Rot(z,\phi)Rot(y,\theta)Rot(x,\psi)$$
$$= \begin{bmatrix} c_{\theta}c_{\phi} & s_{\psi}s_{\theta}c_{\phi}-c_{\psi}s_{\phi} & c_{\phi}s_{\theta}c_{\psi}+s_{\phi}s_{\psi} \\ c_{\theta}s_{\phi} & s_{\psi}s_{\theta}s_{\phi}+c_{\phi}c_{\psi} & c_{\psi}s_{\theta}s_{\phi}-s_{\psi}c_{\phi} \\ -s_{\theta} & s_{\psi}c_{\theta} & c_{\psi}c_{\theta} \end{bmatrix} \quad (2)$$

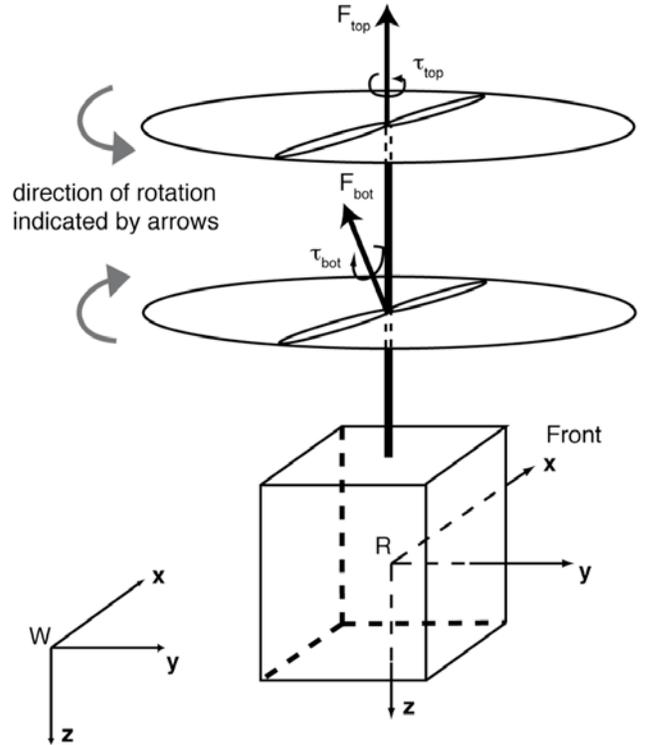where $c_{\alpha} = \cos(\alpha), s_{\alpha} = \sin(\alpha)$.

Figure 4 World frame and robot frame

Force and torque balance

When Lama is in a stable condition, the forces and torques applied are balanced. Unbalance of force will result in linear acceleration ($F = m \cdot a$), while unbalance of torque will result in angular acceleration ($\tau = I \cdot \omega$).

We can consider stable hovering as an example. Force balance is achieved when the sum of the thrust from two

main rotors equals the gravitational force due to the weight of the helicopter (equation 2). That is, all forces and torques in all directions sum to zero.

$$^R F_{top} + {^R F_{bot}} = (m_{top} + m_{bot} + m_{shaft} + m_{body}) * g \qquad (3)$$

The lift forces are generated by rotation of the rotor blades. Blade rotation will cause torque to be applied to the helicopter body. Since the blades are driven to rotate though the air, the aerodynamic drag will also produce opposing torques to the rotor hubs. On the other hand, the gravity force will not generate any torque because Lama can rotote freely around its centre of gravity. In stable hovering condition, the rotor torques should also be balanced (Equation 3).

$$^R \tau_{top} - {^R \tau_{top}^{drag}} = {^R \tau_{bot}} - {^R \tau_{bot}^{drag}} \qquad (4)$$

Inertia

Inertia opposes linear and angular acceleration to stabilize motion. To calculate the moment of inertia of Lama, we need to divide the whole airframe into parts. For simplicity we assume the propellers can be modelled as thin plates, the rotor shaft can be modelled as a thin cylinder, and the helicopter fuselage that contains motor, battery and electronics can be modelled as a solid cuboid of height h, width w, and depth d.

Then the inertia of a blade rotates about its centre is

$$I_{px} = \frac{1}{12} m_{top} l_{radius}^2$$

$$I_{py} = \frac{1}{12} m_{top} l_{chord}^2 \qquad (5)$$

$$I_{pz} = \frac{1}{12} m_{top} (l_{radius}^2 + l_{chord}^2)$$

where l_{radius} is the length of the propeller and l_{chord} is the width of the propeller.

As the blade rotates around one end, we use the parallel axes theorem to calculate the inertia around the centre of rotation. As there are two blades per rotor we can either multiply the inertia by two, if we assume the blades are identical, or add the inertia for its two blades.

Since the size of bottom rotor is the same as the top rotor, it has similar inertia. The blades are made from very light material (1.5 g each) to reduce the inertia and increase the change rate of rotational velocity, which improves the response of Lama to throttle changes.

The top rotor differs from the bottom rotor in having a stabilizer at around 70 degrees to the rotor blades. It contributes an additional inertia to the top rotor of $2 * m_{stab} r_{stab}^2$ with $m_{stab} = 2.5g$ is the mass of each weight.

The inertia of the rotor shaft is

$$I_{sx} = m_{shaft} (\frac{r_{shaft}^2}{4} + \frac{l_{shaft}^2}{12})$$

$$I_{sy} = m_{shaft} (\frac{r_{shaft}^2}{4} + \frac{l_{shaft}^2}{12}) \qquad (6)$$

$$I_{sz} = m_{shaft} \frac{1}{2} r_{shaft}^2$$

where the r_{shaft} is the radius of the shaft and l_{shaft} the length of the shaft.

Then inertial of helicopter fuselage is

$$I_{fx} = \frac{1}{12} m_{body} (h^2 + w^2)$$

$$I_{fy} = \frac{1}{12} m_{body} (h^2 + d^2) \qquad (7)$$

$$I_{fz} = \frac{1}{12} m_{body} (w^2 + d^2)$$

We obtain these equations with the assumption that the centre of gravity is on the concentric line of the rotor shaft. If it is not, then we need to apply the parallel axes theorem to the moment of inertia of the rotors and the rotor shaft with following equation

$$I_{ncg} = I_{cg} + ml^2 \qquad (8)$$

where l is the distance between the new rotational axis and the original rotational axis.

When the centre of gravity is not on the rotor centre line, cyclic pitch will be required to balance the resultant torque reducing its control range. Hence, it is better to balance the load on Lama to minimise the distance from the cog to the rotor centre line.

Dynamics

Because helicopter motions are dominated by the two main rotors, we first need to understand the behaviours of the two rotors in flight before analysing the dynamics of Lama.

Bottom rotor

The bottom rotor is linked to two servos (Figure 3), which control its lateral pitch and longitudinal pitch respectively. Therefore, we can control the cyclic pitch of the bottom rotor to command the Lama to pitch and roll.

To show the force generated by the bottom rotor, we first need to make a few assumptions. To simplify the analysis, we assume that the centre of gravity is on the concentric line of the rotor shaft. Also, for a small helicopter, the lift generated by the propellers can be expressed as

$$|F_l| = \frac{\rho C_l U^2 S}{2} = K_l \omega_{blade}^2 \qquad (9)$$

where ρ is density of the air, $S = l_{radius} * l_{chord}$ is surface area of the blade, U is the flow velocity, C_l is the lift coefficient and ω_{blade} is the velocity of the rotor blades.

A spinning rotor also produces a drag force due to air resistance (Equation 9).

$$\left|F_d\right| = \frac{\rho C_d U^2 S}{2} = K_d \omega_{blade}^2 \tag{10}$$

where C_d is the drag coefficient.

Therefore, the force generated by the bottom rotor can be calculated as

$$\left|F_{bot}\right| = \left|F_{bot}^l\right| - \left|F_{bot}^d\right| = (K_l - K_d)\omega_{blade}^2 = K\omega_{blade}^2 \tag{11}$$
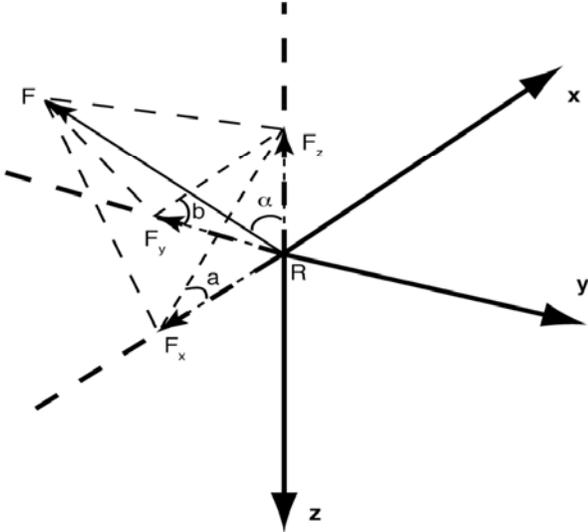

Figure 5 Thrust vectors

Since the purpose of modelling is for controlling Lama, the variables we use should be reflected into control space. Considering there are pitch and roll joystick controls in the transmitter, it is reasonable for us to define a and b the longitudinal and lateral cyclic pitch of the bottom rotor respectively. Notice α is the angle between thrust vector and the z axis, as shown in Figure 5. From simply geometry, we calculate

$$\tan^2 \alpha = \frac{(F_{bot}^x)^2 + (F_{bot}^y)^2}{(F_{bot}^z)^2}$$
$$\tan^2 \alpha = \tan^2 a + \tan^2 b \tag{12}$$
$$\cos \alpha = \frac{\cos a \cdot \cos b}{\sqrt{1 - \sin^2 a \cdot \sin^2 b}}$$

Therefore, F_{bot} can be expressed as

$$^R F_{bot} = T(a,b) \cdot \left|F_{bot}\right| \tag{13}$$

where

$$T(a,b) = \frac{1}{\sqrt{1 - \sin^2 a \sin^2 b}} \begin{pmatrix} -\sin a \cdot \cos b \\ \sin b \cdot \cos a \\ -\cos a \cdot \cos b \end{pmatrix} \tag{14}$$

Top rotor

The top rotor of Lama is not linked to any servo (Figure 2), so we can only control its rotational velocity. With a stabilizer bar attached to the top rotor, it forms a Hiller control system. This control system has the effect of changing blade pitch in reaction to helicopter tilt to slow and stabilize tilt motion.

When hovering, the top rotor disk plane is horizontal and generates a vertical lift force and the stabilizer bar spins in a horizontal plane. In this situation, the pitch of the top blades, which is the angle of blades to the rotor disk plane, is fixed and measurable. If the helicopter pitches due to control input or other interference, the top rotor will try to stay in a horizontal plane due to the inertia of the stabilizer, which results in cyclic pitch of the blades to oppose the helicopter pitch. Therefore, the stabilizer acts like a Proportional Integral (PI) control law to stabilize the helicopter by controlling the change rate of the angle of the top rotor disk.
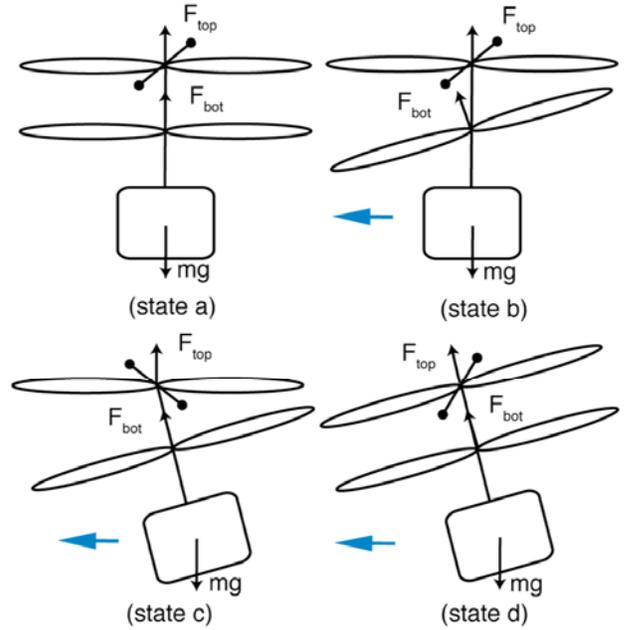

Figure 6 Rotors' instant response to pitch command

As illustrated in state (a) of Figure 6, the forces generated by the two main rotors are balanced with the gravitational force. Their directions are both concentric with the rotor shaft when hovering. In state (b), the bottom rotor pitches in response to a pitch command. The pitch of the bottom rotor will cause torque to be applied to the helicopter body, as the force generated by the bottom rotor is no longer through the centre of gravity. This torque will make the helicopter body pitch as in state (c). At this stage, the top rotor attempts to remain rotating in a horizontal plane due to the inertia of the stabilizer. And since the top rotor now generates a force that does not go through the centre of gravity, this force will cause a torque that opposes the pitch torque to make the helicopter body swing until all three forces go through the centre of gravity again, as in state (d).

Above analysis is the transition procedure of the Lama

from hovering state to forward pitch and translation state. To obtain a dynamic equation that describes the behaviours of the top rotor, we need to consider it within a single state. We know that the top rotor in not linked to any servo, so it only generates a lift force that is along the z axis if the Lama remains in the same state. Therefore, we have

$$^{R}F_{top} = {}^{R}F_{top}^{z} = \begin{pmatrix} 0 \\ 0 \\ |F_{top}| \end{pmatrix} \qquad (15)$$

In state (a), (b) and (d), we have a force through the centre of gravity. In state (c), the top rotor force is not through the centre of gravity, so the total force produce a x (translation) component as well as a z (lift) component.

Torque

Motor torque forces the rotors to rotate against the air, causing the air to move. As the torques that drive the top and bottom rotors are concentric, they balance through the motor gearbox shaft mechanism of the two drive system.

$$^{R}\tau_{top} = {}^{R}\tau_{bot} \qquad (16)$$

If we model the forces on each blade to be acting through its centre, then the torque produces a force on the air is

$$^{R}F_{blad} = \frac{\tau_{top}}{l_{radius}} \qquad (17)$$

The reaction force has two components, one vertical that produces lift and one horizontal that causes drag. The component that produces lift also causes air motion, so these components map to the equation for lift and drag (Equation 9 and 10).

Gyroscopic torque

In hovering condition, the spin axes of main rotors are parallel to the z axis of the robot frame. When Lama rolls or pitches, it changes the directions of momentum vectors of the main rotors. This results in a gyroscopic torque that tries to turn the spin axis to align with the precession axis.

Because the top rotor is not driven, it will automatically change cyclic pitch to balance any forces produced by gyroscopic torque. In contrast, the gyroscopic torque of the bottom rotor will oppose body rotation.

For a roll, the spin is around the z axis (ω_p), the roll rate is around the x axis (ω_x), so the gyroscopic torque of the bottom rotor must be around the y axis.

$$^{R}\tau_{gy} = {}^{R}I_{pz}\omega_p \times \omega_x \qquad (18)$$

Similarly, for pitch the torque is around the x axis.

$$^{R}\tau_{gx} = {}^{R}I_{pz}\omega_p \times \omega_y \qquad (19)$$

No gyroscopic torque occurs with yaw movement because the spin and precession axes remain parallel.

Coriolis and centripetal acceleration

The rotors spin within a plane parallel to the xy plane, so when the Lama yaws the blades of the rotors experience coriolis acceleration. Coriolis acceleration represents the difference between the relative acceleration measured from non-rotating axes and from rotating axes. Because the yaw rate of Lama is relatively slow, we can neglect this acceleration in modelling.

Centripetal acceleration which is the change of the object's velocity vectors among different segments, also acts on the blades. Since the blade material can be considered as rigid under this situation, we can neglect this acceleration in modelling.
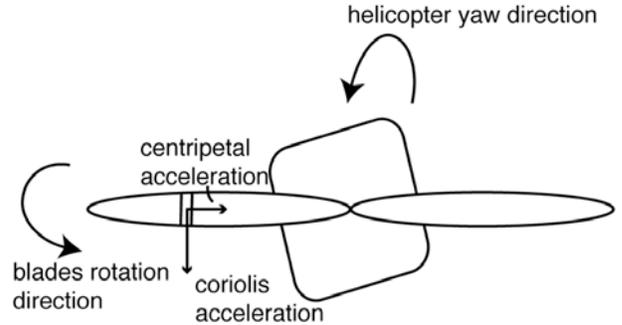

Figure 7 Centripetal and coriolis acceleration – top view

4 Lama vs. Dragonflyer

In a previous paper, we modelled the Dragonflyer [McKerrow, 2004]. The Dragonflyer is a radio-controlled four-rotor helicopter. The operator of the radio controller has four channels of input to control the helicopter motion in six degree of freedom. Unlike a conventional helicopter, where lift force generated by rotors can change direction by modifying the rotor pitch angle, the motion of Dragonflyer can only be controlled by varying the speed of the four rotors, as the pitch angle of rotors is fixed.

Figure 8 Dragonflyer

The Dragonflyer is difficult to control even by a skilled operator. This is partially because of its highly coupled dynamics, but the main reason of Dragonflyer's instability is the deficiency of its structure. As can be seen in Figure 9, lift forces apply to the centre of gravity through carbon fibre frame. The helicopter will remain stable hovering if the four lift forces are the same and the sum of these forces equals the gravity force. However, any difference in rotor speed or rotor pitch angle or rotor size, which has great possibility to happen due to manufacturing inconsistency or assembly fault, can cause force or torque unbalance. And then it will result in pitch, roll and yaw movement of helicopter. This is the reason that Dranganflyer has to use three gyros to provide feedback

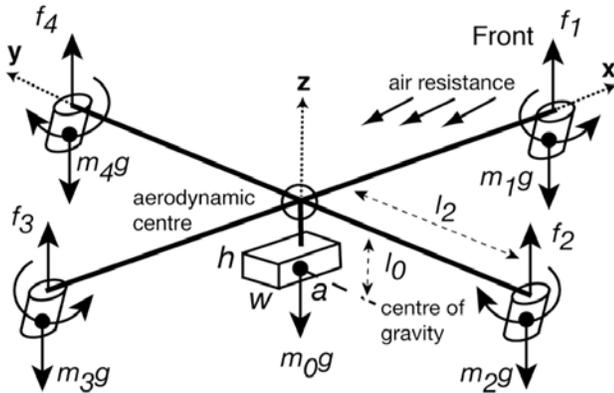for closed loop control to stabilize roll, pitch and yaw.

Figure 9 Force balance of Dragonflyer

In the coaxial helicopter Lama, motion is controlled by the rotor speed difference between the top and bottom rotors and the cyclic pitch of the bottom rotor. In the following analysis, we demonstrate that the coaxial helicopter is a better structure than the four-rotor helicopter by explaining three scenarios. Notice that all scenarios are based on stable hovering condition.

The first situation is that rotor speed is different between top and bottom rotors. In this case, Lama will have yaw movement due to torque unbalance. The yaw channel only has slight coupling with the throttle channel. As long as rotors are producing enough lift, yaw will only change the helicopter's heading. And the helicopter will still remain stable hovering in limited space. Furthermore, yaw movement can be measured and corrected with a yaw gyroscope.

The second situation is a blade pitch angle difference in the same rotor. A rotor consists of two blades. The pitch angle of both blades should be the same in ideal conditions. If the blade pitch angle is not the same, then it will result in vibration because the lift generated is different in each blade. In Lama, this will not cause pitch or roll as the blade is rotating and the greater lift is not always on the same side.

The third situation is a blade pitch angle difference between top and bottom rotors. This will again generate torque difference due to inequality of lift forces and the result is the same as the first situation.

Hence, we can see that manufacturing inconsistency or assembly fault can only cause yaw movement and vibration and not pitch or roll movement of the coaxial helicopter Lama. Also, the torque balance between the rotors occurs through the concentric driveshaft in the Lama, so the torques are localized to the motor gearbox system. But in the Dragonflyer, torque occurs through the airframe placing stresses on the airframe. Therefore, coaxial helicopter is reasonable to be considered as a better-balanced mechanism than four-rotor helicopter.

5   Conclusion

In this paper, we show a model of coaxial helicopter as well as the benefits of coaxial structure with comparison with single-rotor helicopter from a theoretical point of view and with four-rotor helicopter from a mechanical point of view.

Future work includes putting a micro controller and a series of sensors on board and constructing a control algorithm based on the model developed in this paper. Then we can apply this platform to meet the requirements of site assessment task.

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