Control of a Coaxial Helicopter with Center of Gravity Steering

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Abstract. This paper shows roll and pitch feedback control on a coaxial mini helicopter equipped with a center of gravity steering mechanism. The helicopter carries a minimal set of sensors to measure yaw rate, distance to ground and roll and pitch angle. While yaw rate and distance to ground control are already realized on the helicopter, roll and pitch control including the necessary signal filtering are newly developed for the system. Additionally, two feedforward compensations for the distance to ground control are introduced. Flight data shows the performance of the attitude control subjected to external disturbances, and the improvements achieved by the two compensations in distance to ground control.

1 Introduction

Mini and micro helicopters, equipped with suitable sensors and computing power, are excellent platforms to perform indoor search, surveillance or exploration missions. To be mission capable, these helicopters must be able to steer horizontally to follow a desired flight path and avoid obstacles. The mere capability to hover is clearly not enough.

Today, horizontal steering for mini and micro helicopters is almost exclusively achieved by a change of the orientation of the main rotor's tip path plane with respect to the helicopter fuselage [1]. This change is typically effected by use of a swash plate mechanism to apply cyclic pitch to the rotor blades [2]. Recent research has investigated possibilities to change the orientation of the complete helicopter instead of only that of the tip path plane. Possible solutions are a reorientation of the rotor air flow by use of flaps [3] or a ducted fan [4], or displacing the helicopter's center of gravity (CoG) to achieve a steering moment on the fuselage effected by the rotor thrusts [5, 6]. The advantage of these steering principles compared to a swash plate are a greater design freedom (servo motor placement) and in general a greater potential for miniaturization, the latter being largely driven by the growing demand for micro helicopters. In this research, we focus on steering by displacing the helicopter's CoG.

For our work we use the coaxial helicopter CoaX 2 [6] with an improved, more effective CoG steering mechanism [7]. Although classified as a mini helicopter, it is a good demonstrator for the CoG steering principle. Simple PD feedback

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control for the distance to ground and the helicopter yaw rate are already implemented. The CoG steering mechanism, however, can only be operated in open loop with commands coming from a pilot. The goal of this work is to implement roll and pitch feedback control relying on onboard computing power and with information gathered from onboard sensors, in contrast to [5], but also without position control. Additionally, the existing distance to ground control is refined to compensate for the variation in the distance to ground information as a result of helicopter (and thus sensor) roll and pitch motion.

The paper is organized as follows: in Section 2, the CoaX 2 helicopter platform is introduced in terms of rotor configuration, steering device, sensor layout and onboard computational resources. In Section 3, the newly implemented roll and pitch angle control is shown. Section 4 describes the enhancement of the existing distance to ground control to compensate for helicopter roll and pitch motion. It is followed by experimental results obtained with the new control in Section 5.

2 Hardware and electronics

The CoaX 2 helicopter is a mini helicopter in coaxial rotor configuration (see Fig. 1 left). It has a rotor diameter of 335 mm and a total mass of 230 g. The rotor system is taken from a Hirobo X.R.B Lama toy helicopter [8] and is driven by two brushless DC motors. The helicopter is powered by a lithium polymer battery with a capacity of 910 mAh, which allows for a flight autonomy time in hover of about ten minutes.

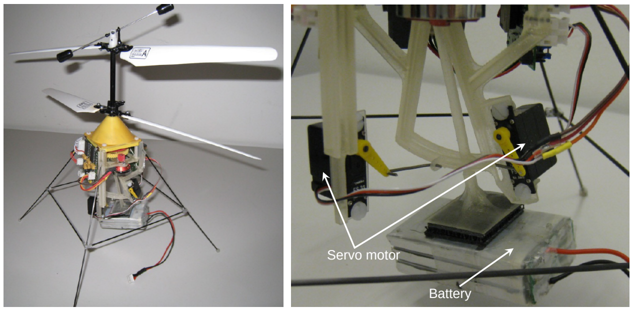

Fig. 1. CoaX 2 helicopter (left) and CoG steering mechanism with battery (right).

The helicopter is steered by a CoG steering mechanism that displaces the helicopter's battery in a spherical section work space (see Fig. 1 right). The mechanism is actuated by two robbe FS31 servo motors. With a battery mass of 70 g, roughly one third of the total mass is displaced with a maximum projected stroke of 20 mm in the helicopter fixed x– and y–directions. This leads to a sufficient steering input for horizontal translation of the helicopter [7].

The electronic and sensor layout of CoaX 2 is largely similar to the initial layout

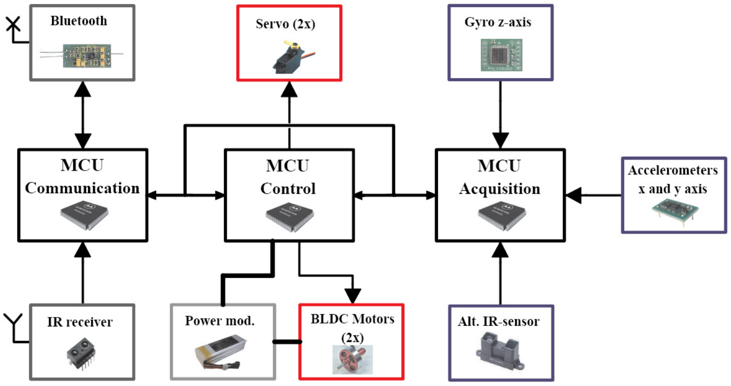

Fig. 2. Electronic and sensor layout of the helicopter.

described in [6] and is shown in Fig. 2. The helicopter carries a two axis inclinometer [9] to measure roll and pitch angles, and a one axis MEMS gyro [10] to measure the yaw rate. An infrared ranging sensor [11] measures the distance to ground. To prevent interference with the steering mechanism, the infrared sensor's optical axis is inclined 40° from the helicopter's yaw axis.

Ground station communication is provided via Bluetooth connection. With a ground station graphical user interface, commands are transmitted to the helicopter and sensor information from the helicopter is received and stored. Additionally, pilot commands can be given via infrared remote control.

In terms of computational power, the helicopter carries three 8-bit micro controller units (MCU) [12], one for actuator control, one for sensor data processing and one for ground communications. The onboard control loop runs at a frequency of 50 Hz.

3 Roll and pitch angle control

To achieve feedback control on the roll and pitch angles of the helicopter, a very simple control structure is chosen. Assuming that both angles are only very weakly coupled, we treat them as decoupled states and design two separate control loops in our control structure (Fig. 3). The digital filtering of the inclinometer data is necessary because the sensor output signal is very noisy due to helicopter vibrations in flight.

For the selection of a suitable filter, a compromise between filtering quality and the available onboard computing power needs to be found. Therefore, three different filters are investigated, a Blackman window filter, a Butterworth filter and a running–sum low pass filter [13]. While Blackman can be used for online filtering on the helicopter, the filtering quality is poor and shows no obvious signal improvement. In contrast to that, Butterworth achieves a significant signal improvement. However, it is computationally very expensive on the helicopter's

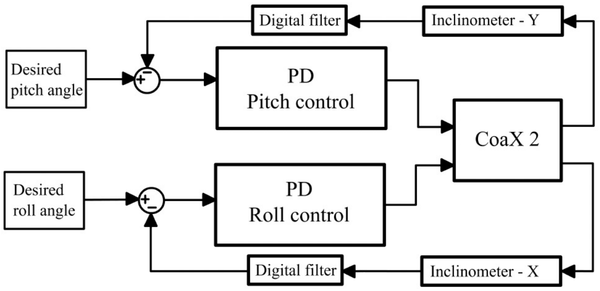

Fig. 3. Roll and pitch control block diagram.

micro controllers and not suitable for online filtering at 50 Hz. A good compromise is the running–sum low pass filter. We use it in its weighted form as

$$y(t) = \frac{1}{10}x(t) + \frac{9}{10}x(t - t_{\mathrm{S}}). \tag{1}$$

The current filtered value, $y(t)$, corresponds to the sum of 10 % of the current unfiltered value, $x(t)$ and 90 % of the previously sampled unfiltered value $x(t - t_{\mathrm{S}})$, where t_{S} is the sampling time. An unfiltered and a filtered pitch angle signal are shown in Fig. 4. It can be seen that the filtered signal is smoother and less noisy than the unfiltered signal, while the filter can still be run at 50 Hz. In the experimental results we will show that the remaining level of noise is sufficient to allow for successful flight experiments.

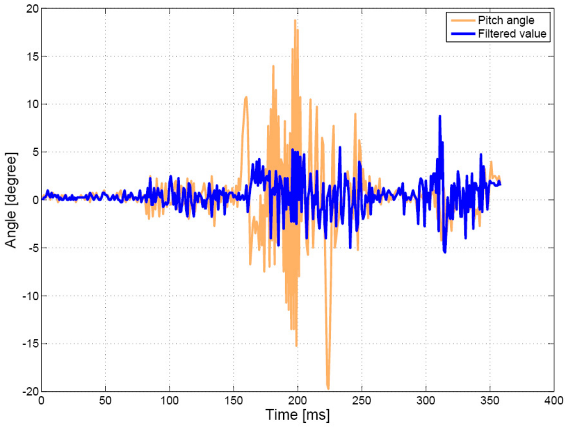

Fig. 4. In flight inclinometer output (orange) and filtered signal (blue) of the weighted running average filter.

Corresponding to Fig. 3, PD control is chosen for the feedback loops in roll and pitch. The control parameters are manually tuned to $k_P = 1$ and $k_D = 0.33$.

4 Distance to ground control

An existing distance to ground feedback control is enhanced to make it compatible with the helicopter's changed flight envelope: prior to the installation of the steering mechanism, the helicopter has been flown without roll and pitch inputs. Due to the passive horizontal attitude stability of the system, only small roll and pitch angles occurred, making a calculation of the true distance to ground from the inclined infrared sensor data possible by using the small angle assumption. Due to the higher roll and pitch angles occurring in steered flight, this assumption holds no longer true. Therefore, the calculation of the true distance to ground needs to be modified:

$$h_{\text{true}} = h_{\text{meas}} \cos(40^\circ - \phi) \cos(\theta), \tag{2}$$

where h_{true} is the helicopter's distance to ground, h_{meas} is the distance measured by the infrared sensor, ϕ is the roll angle and θ is the pitch angle. Figure 5 (left) shows the effect of this compensation function. The data is measured on the helicopter, however, tilted by hand. It is obvious, that helicopter inclinations around roll and pitch affect the distance to ground measurement, while the compensated measurement remains unaffected.

In a similar manner, the two rotor speeds are adapted to helicopter inclinations.

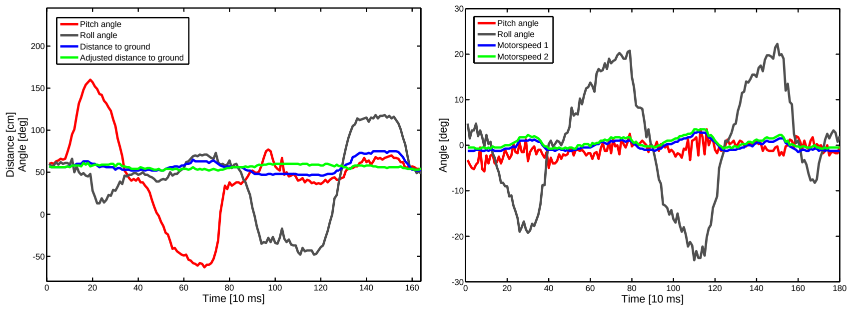

Fig. 5. Left: Uncorrected (blue) and compensated (green) distance to ground measurement for helicopter roll and pitch motions. **Right:** Compensated motor speeds (blue and green) for helicopter roll motions.

This is necessary because the two rotor tip path planes and their respective perpendicular thrust vectors are tilted with the helicopter, resulting in a thrust vector component that is perpendicular to the gravity field. This results in a loss of altitude, if the rotor speeds are not increased. Due to higher resolution of the inclinometer compared to the infrared sensor, a faster response can be achieved by a roll and pitch angle dependent compensation of the rotor speeds:

$$\Omega = \frac{\Omega_{\mathrm{ctrl}}}{1 + \arctan\left(\sqrt{(\tan\phi)^2 + (\tan\theta)^2}\right)}, \tag{3}$$

where Ω is the rotor speed corrected by the helicopter inclination, and Ω_{ctrl} is the rotor speed output of the distance to ground PD controller. The result of this compensation is shown in Fig. 5 (right). With every variation of the roll angle, the motors speed up to compensate for the imminent loss of altitude as described before.

These two compensation functions contribute observably to the quality of the helicopter's distance to ground control.

5 Flight test results

The implemented controllers are tested in flight experiments. The performance of the attitude PD control using the CoG displacement mechanism, and the refined distance to ground control with the aforementioned compensations are examined.

5.1 Roll and pitch control

In Fig. 6, flight data for a test flight with roll and pitch control turned off is shown. The helicopter's pitch angle is disturbed two times (at 97 seconds and 106 seconds). Although feedback control is turned off, the helicopter returns to its initial neutral hovering attitude in about 0.5 seconds. This is due to the fact that the helicopter is designed passively stable in roll and pitch.

For comparison, flight data for a test flight with roll and pitch control turned on is given in Fig. 7. Additionally, the servo motor actions are plotted. The roll and pitch angle set points are set to 0°. Here, again the pitch angle is disturbed twice (71 seconds and 80 seconds). The data shows the reaction of the control to the pitch angle disturbances. It can be observed that the helicopter returns to its neutral hovering attitude in about 0.25 seconds, a shorter period of time than in open loop flight. The active control of the CoG displacement mechanism supports the passive stability of the helicopter and leads to a faster return to a neutral attitude. The response of both servos to the pitch disturbance is owed to the fact that the steering mechanism is rotated by 45° around the helicopter fixed yaw axis.

5.2 Distance to ground control

Figure 8 shows ten seconds of flight data with distance to ground control and the two compensations turned on and a set point distance of 60 cm. At about

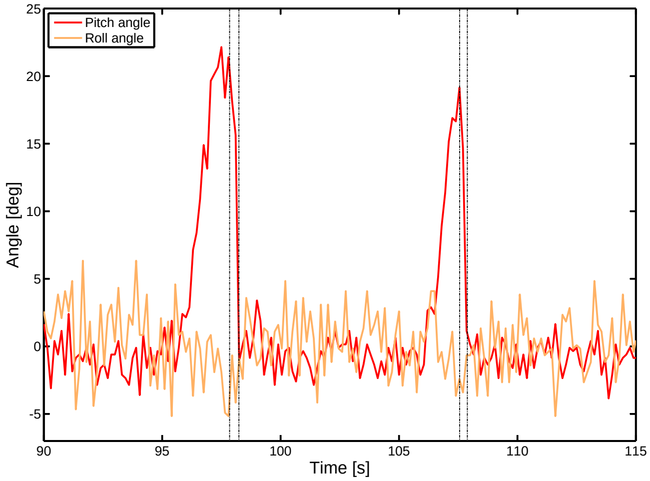

Fig. 6. Roll (light red) and pitch (red) angle in open loop flight. Pitch angle disturbed at 97 seconds and 106 seconds.

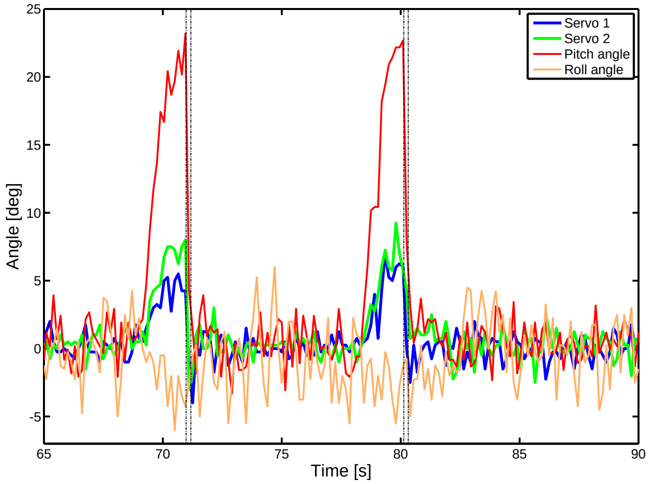

Fig. 7. Roll (light red), pitch (red) angle and servo motor signals (blue and green) in closed loop flight. Pitch angle disturbed at 71 seconds and 80 seconds.

58 seconds the helicopter rolls left by about 20°, while the pitch angle is kept at a constant value. As the data shows, during that maneuver the distance to ground remains almost constant. The two compensations in connection with the PD control show effective action.

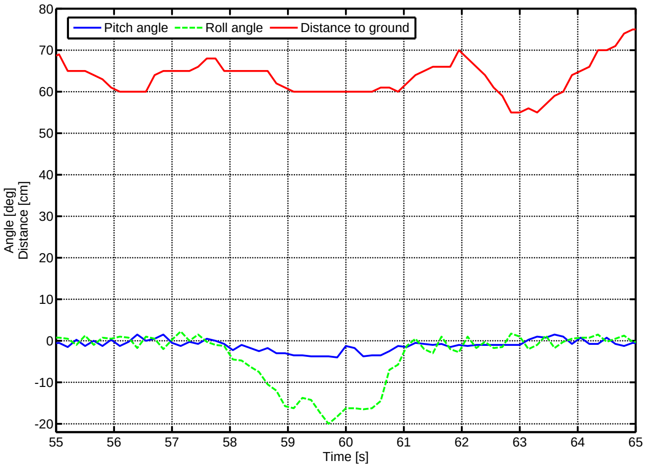

Fig. 8. Distance to ground (red), pitch (blue) and roll (green) angle measured in flight. Roll left maneuver at 58 seconds.

6 Summary and Conclusions

In this paper we show the implementation of horizontal attitude control on a mini coaxial helicopter with a CoG displacement steering mechanism. The sensors used for control are a two axis inclinometer, an infrared distance to ground sensor and a one axis MEMS gyro. All control algorithms are run on an 8-bit micro controller unit, thus have to be simple and computationally effective.
For the horizontal attitude control, the control structure for two independent PD controllers for the roll and pitch angle is introduced. Due to the moderate quality of the sensor data, digital filtering is unavoidable. We select a weighted running average filter to find the best compromise between filtering quality and computational effort. With the filtered sensor data, the PD control for horizontal attitude is successfully tested in flight. Despite the passive stability of the helicopter in roll and pitch, the feedback control improves the system's disturbance rejection capability. The time no neutralize a disturbance is reduced by approximately 50 %.
For an existing altitude control, two compensations are introduced. They become necessary due to the larger roll and pitch angle amplitudes of the helicopter as a result of the steering mechanism. Basically, these compensations are feedforward controls based on the horizontal pose of the helicopter. Their contribution

is clearly visible in experimental data and enhances the altitude control loop. Future work will investigate the possibility of reducing the passive stability margin with compensation by the active horizontal attitude control.

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