Simple physics behind the flight of a drone

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Abstract
The flight of a quadrorotor drone, readily available as a toy, is analyzed using simple physics concepts. A smartphone with built-in accelerometer and gyroscope was attached to the drone to register the accelerations and angular velocities along the three spatial axis while the drone is taking off, landing or rotating. The vertical speed, the height and one of the angular coordinates are obtained through numerical integration of the acceleration values and compared with information provided by the manufacturer. The analysis of these quantities provides an opportunity to gain insight into important physics concepts involving Newton laws and conservation principles in a stimulating environment.

Keywords: sensor, drone, smartphone, accelerometer, gyroscope

1. Drones and physics
Remotely-controlled helicopters and planes have been available as toys for decades. However, only recently, advances in sensor technologies have made it possible to easily fly and control these devices at an affordable price [1]. Along with their increasing availability the educational opportunities are also proliferating [2, 3]. In a previous experiment we measured the height and pressure in the inner layer of the atmosphere using a smartphone mounted on a drone. These kinds of measurements can be compared with approximate models such as an isothermal or a constant density atmosphere and also with the International Standard Atmosphere [4]. Here, a simple experiment in which a smartphone was mounted on a drone is described, which investigates the basics of flight. Thanks to the smartphone’s built-in accelerometer and gyroscope, the linear and rotational kinematics of the aircraft in take-off, landing and yaw can be analysed. To get a deeper insight, the acceleration values were numerically integrated using a simple scheme to obtain the vertical speed and height. The measured maximum value of the vertical speed can be compared with the manufacturer’s specifications.

2. The outdoor experiment
A smartphone, model LG G2, was mounted on a radio-controlled a DJI Phantom 2 quadcopter using an arm band case as shown in figure 1. Several simple flights were accomplished consisting....
of ascents and descents with constant speed or constant acceleration and different trajectories at constant height (circles, ‘U’ or ‘S’ shaped). During these flights, the smartphone’s sensors recorded the acceleration and the angular velocity using the Androsensor application. In practice, after several minutes of collecting data, it was difficult to discern which portion of the graph corresponds to a particular manoeuvre. To avoid this problem a video camera, or a second smartphone, was used from the ground to record alternatively the flight and the operation of the remote control. In what follows, we focus on some of the records of the sensors and analyse the acceleration and angular velocity along the vertical axis.

3. The drone’s flight
The drone’s flight is based on the rotation of four vertical axis propellers (rotors) arranged in the corners of a square. As a result of the Newton’s second law, when the drone is hovering at constant altitude the upwards thrust generated by the rotors equals the downward gravitational force on the airframe. A vertical acceleration or deceleration is obtained thanks to an increase or decrease of the total power of the rotors. If the thrust force is upwards and exceeds the force of gravity, then the drone will initially accelerate, however, in doing so its potential energy increases, and the motors have to do work to supply that energy. So, the rate of rise will be limited to the rate at which the motors can deliver this energy.

The vertical acceleration as a function of time is shown in figure 2. Initially the drone is turned off on the ground. After a few seconds, the vehicle is switched on and the propellers start to spin. The vibrations induced by the propellers are clearly detected by the accelerometer. Then, the drone takes off as revealed by an upward acceleration. It is also worth mentioning that the vertical acceleration does not reach its maximum value immediately but it takes an interval of about 1 s before that. After an interval of deceleration, the drone is kept hovering for a few seconds. Note that the acceleration values registered by the sensors are not centered about 0 but about 10 m s$^{-2}$. In the accelerometer essentially the force required to hold a mass in a fixed position relative to the smartphone is being registered. In accordance with Newton’s second law this force is proportional to the acceleration. At the same time, quite independently, the mass is being acted on by a completely different force of 10 N kg$^{-1}$ downwards due to the mutual gravitational attraction of the mass in the instrument and the mass of the Earth. Because the gravity force per unit mass cannot be distinguished from the acceleration force in this instrument (or indeed by anyone blindfolded in an aircraft), it appears as a fictitious acceleration (of 10 m s$^{-2}$, which is exactly the same thing as 10 N kg$^{-1}$) in the direction away from the centre of the Earth. This fictitious acceleration...
also appears in other smartphone experiments as the physical pendulum [5, 6]. It is also worth noting that the registered vertical acceleration is greater than \(10 \text{ m s}^{-2}\) at the take off. Nevertheless, a few seconds later when the device decelerates it is less than \(10 \text{ m s}^{-2}\).

The landing and a subsequent take off of the drone is analyzed in figure 3. During the first stage the device is accelerating downward, then the acceleration registered is less than \(10 \text{ m s}^{-2}\). To avoid an abrupt landing, the drone is kept hovering close to the ground and smoothly landed at \(t = 174\) s. After about 20 s a new take off is accomplished. As a consequence of the stabilization mechanism of the drone when it is ascending or descending at constant speed or hovering the acceleration measurements are very noisy and special care should be taken to numerically integrate the acceleration to obtain the velocity or the altitude [7]. The origin of the noise can be associated to several sources. On the one hand, there are contributions mainly due to the interaction of the propellers with the air and the air with the ground, generating turbulence and vibrations evidenced in the increase of the noise at the starting time indicated in the figure. On the other hand, when the drone takes off its stabilization system responds to the atmospheric conditions, leading to an additional rise in the vibrations registered by the smartphone accelerometer.

Generally speaking, the design of a drone is based on the rotational dynamics of the rotors and involves subtle aspects. When the rotation axis is parallel to the spin axis, torque is generated in the airframe by various effects, in particular, due to rotational inertia and also as a reaction to the force needed to overcome the air resistance and to push it downwards. The ability to deliver power to each rotor independently provides the possibility to control the drone. As a consequence of the conservation of angular momentum, to maintain the angular velocity of the device, the sum of the torques generated by the four rotors must be zero. If it is not the case, the device will undergo accelerating vertical-axis rotation. In particular, yaw (rotation about the vertical axis of the machine) is obtained increasing the power in one pair of diagonally opposite rotors and decreasing the power in the other pair to maintain constant lift. The horizontal flight is based on a similar mechanism. To fly forward or backward a horizontal component of thrust is achieved by increasing the rotation rate of two adjacent rotors (the rear ones) and a decreasing of the other two (the front ones). In this situation, the greater force in the back leads the drone to tilt forward, resulting in the thrust force having a horizontal component.

The results obtained by the rotation sensor are depicted in figure 4. Yaw, both clockwise and counter-clockwise (see from above), is easily distinguished in the vertical component of the angular velocity. The maximum values attained by the angular velocity can be compared with other smartphone experiments as the physical pendulum [5, 6].
those provided by the manufacturer. In our model the technical specification indicates $200^\circ \text{s}^{-1} \sim 3.49 \text{ rad s}^{-1}$ which agrees very well the maximum values observed in the figure.

4. Vertical speed, height and angle

Using the vertical component of the acceleration it is possible to integrate numerically these value to obtain, firstly, the vertical speed, and, then, the height as shown in figure 5. This procedure is similar to those proposed in other contexts [5, 8, 9]. As the drone speed control was set at maximum during a time interval the vertical speed attained was the maximum possible for this device model. In our case, the maximum ascent speed reported by the manufacturer was 6 m s$^{-1}$ which agrees very well with that obtained numerically as it can be seen in the figure. In case of having a large and clear space it is also possible to supplement these results with video analysis [10].

Another exercise consists in numerically integrating the vertical angular velocity to obtain the rotation angle in a horizontal plane. The numerical result is shown in figure 4 (bottom). Notice that this can be easily done when the rotation is uniaxial, however, when the drone is rotating along two or three axis this task is very difficult.

5. Conclusion

This experiment, which can be easily replicated in a school yard, provides an interesting opportunity to understand basic concepts in aerodynamics by using the smartphone’s sensors and analyzing their results. The relationships between various kinematic quantities, such as the acceleration,
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velocity, displacement, angular velocity, and angle, can be further investigated using numerical methods. With this simple experiment we exploit the educational capabilities provided by two expanding technologies: drones and smartphones.

Data availability statement
The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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