Quadcopter Drones – Beyond the Hobby

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***Abstract* — This Research to Practice Full Paper presents a teaching approach that preserves depth of knowledge in an environment that seems to fit present learners' technological inspirations and mode of acquiring information. The computer era and the rapid advances in information and communication technologies are imposing significant changes in both teaching and learning styles. Teaching methodologies that are textbook based with long-span intensive analytical hand-manipulations are shifting to electronic sources of information with short-span traditional manipulations. This shift presents a challenge in reaching the balance needed to match teaching to learning styles, without compromising the necessary depth in knowledge.**

The adopted teaching technique is demonstrated via a systematic approach to mathematical modeling and simulation of quadcopter drones. This presents an example of the shift in the teaching/learning style paradigm. Teaching concepts are put into practical use through a methodical utilization of Matlab/Simulink engineering software tools.

Keywords— teaching; learning; technology; drones; Matlab/Simulink; modeling; simulation

I. Introduction

Rapid advances in information and communication technologies are changing not only the way knowledge can be gained but also affecting human behavior and the ways perceptions are formed. Availability of information online and at a person's fingertip, has provided reassurances that are true sometimes but also can be false in many situations. Patience in attaining knowledge and attention spans seem to become less while expectations and achievement levels are perceived to be rising. The challenge is always in reaching a balance that takes advantage of new technologies without compromising the depth in acquired viable knowledge, which is critical for long-term achievements. Researchers concluded that today's young learners take technology for granted and staying connected is a central part of their lives [1]. They also found that "doing is more important than knowing, and learning is accomplished through trial and error as opposed to a logical and rule-based approach" [2]. This kind of behavior usually promotes more interest in hands-on activities, which is becoming more evident in recent students' skills. Similarly, Paul Hagner found that these students not only possess the skills necessary to use these new communication forms, but there is an ever increasing expectation on their part that these new communication paths be used [3]. Quick searches can produce ample material that users may jump into utilizing without fully understanding how things may fit together. The outcome in many cases is a product that may seem to work, while it lacks critical thinking and confidence in the proper use. With that said, no one can deny the effectiveness of available technological tools in solving complex problems, when used properly. In a teaching and learning environment, the burden typically lies on the educator to adapt teaching methodologies to the current style of learning.

In summary, advances in information technologies have softened the barrier between perceiving and achieving, in the mind of many learners. Today's leaners are far less intimidated by available tools, as they are ready to try them before taking the time to grasp how they are best utilized. Making errors has become acceptable, by learners, knowing that incremental improvising is a valid approach. While some results may emerge, the line of thought and an initial well thought-out approach could have been compromised. The challenge remains to be as to how to preserve critical thinking in such a technologically evolving environment.

Drones have become very popular as a hobby as well as for industrial, commercial, and military applications. The quadcopter drone in particular is probably among the most desired for exploring and utilization advanced theoretical concepts. One may introduce the quadcopter with emphasis on the utilized technologies, but engineering emphasis require a deeper understanding of the mathematical model and the integration of components. While the subject attracts attention among students and it raises the motivation level, the way of presenting complex concepts remains to be a challenge. The use of such applications along with current technological tools seems to harmonize teaching and learning styles.

This paper provides a systematic and easy to follow methodology to introduce advanced theoretical concepts through the modelling and simulation of quadcopters; as one example of a teaching material that requires depth in knowledge. Incorporating this methodology in teaching has increased learners' attention span and minimized trial-and-error approaches. This teaching methodology can be adopted in teaching other theoretical concepts while utilizing other applications as well.

II. Quadcopter Model

A. Basic Motions

The quadcopter has four propellers; two opposing ones rotate clockwise while the other two rotate counterclockwise, Fig. 1. Adjusting propellers' speed causes translational motion in XYZ as well as roll (γ), pitch (β) and yaw (α). The thrust determines the lifting capability and dynamic motion. The thrust of each propeller can be determined by (1); where F is the thrust, ω is the angular velocity, and k_f is a parameter that is

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dependent on the air density, blade area, and the aerodynamics coefficient.

$$F=k_f\,\omega^2 \tag{1}$$

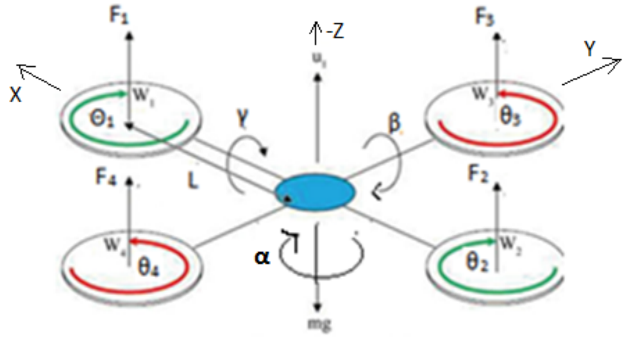

Fig. 1. Quadcopter degrees of freedum

Use of the physical body of the quadcopter for explanation proved to be effective in clarifying the basic motions while attracting students' attention. At this early stage of introducing the subject, learners can be eager to fly the drone and test it for basic motions. This curiousty has to be harnesed until the mathematical model is fully undertood. A sharper eye can usually emerge when field testing finally takes place.

B. Kinematics

The relationship between control signals and propellers' angular velocities (ω_i) is given by (2); where u_1, u_2, u_3, and u_4 are the lift, roll, pitch, and yaw control signals, respectively. This equation is based on (1) and the relative effect of the different propellers on each motion. It should be noted that k_f relates the control signals directly to the propellers' forces and km relates propellers' forces to the rotational moments.

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} k_f & k_f & k_f & k_f \\ 0 & 0 & -k_f & k_f \\ k_f & -k_f & 0 & 0 \\ -k_m & -k_m & k_m & k_m \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{2}$$

The moments of rotation (roll, pitch, yaw) are given by (3); where L is the length of each of the four quadcopter arms.

$$M_B = \begin{bmatrix} Lu_2 \\ Lu_3 \\ u_4 \end{bmatrix} \tag{3}$$

From (2), the angular velocities that correspond to the control signals are determined by (4).

$$\begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} = \begin{bmatrix} \frac{1}{4k_f} & 0 & \frac{1}{2k_f} & \frac{-1}{4k_m} \\ \frac{1}{4k_f} & 0 & \frac{-1}{2k_f} & \frac{-1}{4k_m} \\ \frac{1}{4k_f} & \frac{-1}{2k_f} & 0 & \frac{1}{4k_m} \\ \frac{1}{4k_f} & \frac{1}{2k_f} & 0 & \frac{1}{4k_m} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \tag{4}$$

Using (4), one can determine how fast each propeller must rotate to achieve a given motion command. The calculated rotation angles and moments, would then determine the dynamic motion of the copter based on its inertia and drag parameters. The learner can then start to see how the basic motions are tied to the kinematics of the copter and how this may lead to the dynamic behavior.

C. Dynamics

Equation (5) determines the rotors' relative angular velocity (ω_r), which affects rotational motions.

$$\omega_r = \omega_1 + \omega_2 - \omega_3 - \omega_4 \tag{5}$$

Equation (6) relates the control signals (u_2, u_3, u_4) to the propellers' angular velocities and the roll, pitch and yaw angles (γ, β, α); where I_{xx}, I_{yy} and I_{zz} are the copter's inertia constants about X, Y and Z; respectively. Also, J_r is the rotors' inertia constant for the propellers' driving motors. Therefore, this equation ties the tilt motion of the copter to the control signals. This equation is derived from the basic rotation principles of free bodies in space.

$$\begin{bmatrix} I_{xx}\ddot{\gamma} \\ I_{yy}\ddot{\beta} \\ I_{zz}\ddot{\alpha} \end{bmatrix} + \begin{bmatrix} \dot{\beta} I_{zz}\dot{\alpha} - \dot{\alpha} I_{yy}\dot{\beta} \\ \dot{\alpha} I_{xx}\dot{\gamma} - \dot{\gamma} I_{zz}\dot{\alpha} \\ \dot{\gamma} I_{yy}\dot{\beta} - \dot{\beta} I_{xx}\dot{\gamma} \end{bmatrix} + \begin{bmatrix} \dot{\beta} J_r\,\omega_r \\ -\dot{\gamma} J_r\,\omega_r \\ 0 \end{bmatrix} = \begin{bmatrix} Lu_2 \\ Lu_3 \\ u_4 \end{bmatrix} \tag{6}$$

The learner can now see how the mathematical model is progressing to determine the tilt motion of the copter due to the control signals provided by the operator of the copter. To complete the picture, the location of the copter in the XYZ needs to be added (7); where g is the gravity constant (9.8 m/s^2), c for "Cosine" and s for "Sine" trig functions, and F_{th} is the summation of the four propellers' thrust forces.

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \begin{bmatrix} c\beta c\alpha & s\gamma s\beta c\alpha - s\alpha c\gamma & c\gamma s\beta c\alpha + s\gamma s\alpha \\ c\beta s\alpha & s\gamma s\beta s\alpha + c\gamma c\alpha & c\gamma s\beta s\alpha - s\gamma c\alpha \\ -s\beta & s\gamma c\beta & c\gamma c\beta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -F_{th}/m \end{bmatrix} \tag{7}$$

Knowing the roll, pitch, and yaw angles from (6), one can then determine the XYZ location of the copter.

The above-developed mathematical progression clarifies to the learner how the control signals may produce tilt and XYZ motions. Establishing this model allows the learner to assume remote control/joystick commands to orient and move the copter in space. Automating the motion of the copter and adding unmanned actions would require adding sensory and automatic control algorithms through control theory.

III. COMPUTER SIMULATION

Matlab software is the adopted tool to test the quadcopter's mathematical model and demonstrate the different motions. This activity enables learners to visualize the abstract concepts of mathematical modeling. It also satisfies their curiosity by exploring the limitations of basic motions. It is helpful to give a Matlab demonstration (without going through the exact code), even before developing the mathematical model. This usually motivates the learner and explains why the mathematical model must be developed first. This breaks the barrier of abstractness of the required mathematics and it also highlights the value of going through it.

In addition to demonstrating the basic moves, fundamental concepts start to emerge very quickly. One of the eye-catching examples is the inability of the copter to hold altitude when it tilts, unless the lift control (u_1) is increased. This goes back to the fact that the propellers' forces are perpendicular to the surface of the copter. When the copter is hovering flat, the total thrust force (F_{th}) is equal to the gravity force due to the weight of the copter. As soon as the copter tilts, F_{th} loses its vertical alignment with the gravity force and its vertical component (effective thrust) becomes less. This results in losing altitude because the gravity force exceeds the effective thrust. This phenomenon becomes more critical with the increase in the tilt angle. With a tilt close to 90 deg, the effective thrust component is practically zero and the copter falls very rapidly. While this concept may be explained in developing the mathematical model, observing it on the simulator gives a deeper understanding and it increases the desire to further understand the mathematical model.

The other concept that is well reinforced by simulation is the necessity of tilting to produce horizontal motion. While a tilt reduces the vertical thrust, it creates a horizontal thrust. This component of F_{th} is what produces horizontal motion, which works against the aerodynamics drag force.

Figures (2), (3) and (4) show the basic code for the equations of the copter. Integrating this code into a simple for-loop to increment "i" for the desired time span of flying, the motion of the copter can be observed. The initial parameters will also need to be added at the beginning of the code. For an example, the following typical copter parameters can be used [4]: Ixx=7.5e-3; Iyy=7.5e-3; Izz=1.3e-2; L=0.23; m=0.65; g=9.81; Jr=6e-5; km=7.5e-7; kf=3.13e-5.

```
omega1_sq(i)=((0.25/kf)*u1+(0.5/kf)*u3-(0.25/km)*u4);
omega1(i)=sqrt(omega1_sq(i));
omega2_sq(i)=((0.25/kf)*u1-(0.5/kf)*u3-(0.25/km)*u4);
omega2(i)=sqrt(omega2_sq(i));
omega3_sq(i)=((0.25/kf)*u1-(0.5/kf)*u2+(0.25/km)*u4);
omega3(i)=sqrt(omega3_sq(i));
omega4_sq(i)=((0.25/kf)*u1+(0.5/kf)*u2+(0.25/km)*u4);
omega4(i)=sqrt(omega4_sq(i));
F1=kf*omega1_sq(i);F2=kf*omega2_sq(i);...
    F3=kf*omega3_sq(i);F4=kf*omega4_sq(i);
Fth=(F1+F2+F3+F4);
Mb=[L*u2;L*u3;u4];
```

Fig. 2. Matlab code for (3) and (4)

To display the motion of the copter, one may plot x, y, z, gama (roll), beta (pitch), alpha (yaw) versus time. Also, a three-dimentional XYZ plot would show the motion of the center of the copter in space. Animation commands are also available to show the XYZ motion as time progresses.

Figs. 5 and 6 show the motion of the copter for the following set of control signals: u1=m*g; u2=0.7; u3=0; u4=0. The drop in altitude is evident while the copter is rolling (u2 command). Also, the corresponding horizontal motion in the y-direction is evident.

```
omegar=omega1(i)+omega2(i)-omega3(i)-omega4(i);
gama_ddot(i)=(1/Ixx)*((-beta_dot(i)*(Izz-Iyy)...
    *alpha_dot(i))-(beta_dot(i)*Jr*omegar)+Mb(1));
gama_dot(i)=dt*gama_ddot(i)+gama_dot(i-1);
gama(i)=dt*gama_dot(i)+gama(i-1);
beta_ddot(i)=(1/Iyy)*((-alpha_dot(i)*(Ixx-Izz)...
    *gama_dot(i))+(gama_dot(i)*Jr*omegar)+Mb(2));
beta_dot(i)=dt*beta_ddot(i)+beta_dot(i-1);
beta(i)=dt*beta_dot(i)+beta(i-1);
alpha_ddot(i)=(1/Izz)*((-beta_dot(i)*(Iyy-Ixx)...
    *gama_dot(i))+Mb(3));
alpha_dot(i)=dt*alpha_ddot(i)+alpha_dot(i-1);
alpha(i)=dt*alpha_dot(i)+alpha(i-1);
```

Fig. 3. Matlab code for (5) and (6)

```
x_ddot(i)= -(Fth/m)*((cos(gama(i))*sin(beta(i))...
    *cos(alpha(i)))+(sin(gama(i))*sin(alpha(i))));
x_dot(i)=dt*x_ddot(i)+x_dot(i-1);
x(i)=dt*x_dot(i)+x(i-1);
y_ddot(i)= -(Fth/m)*((cos(gama(i))*sin(beta(i))...
    *sin(alpha(i)))-(sin(gama(i))*cos(alpha(i))));
y_dot(i)=dt*y_ddot(i)+y_dot(i-1);
y(i)=dt*y_dot(i)+y(i-1);
z_ddot(i)= g-(Fth/m)*(cos(gama(i))*cos(beta(i)));
z_dot(i)=dt*z_ddot(i)+z_dot(i-1);
z(i)=dt*z_dot(i)+z(i-1);
```

Fig. 4. Matlab code for (7)

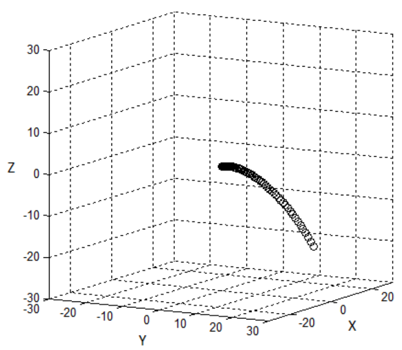

Fig. 5. Copter XYZ motion for a roll command

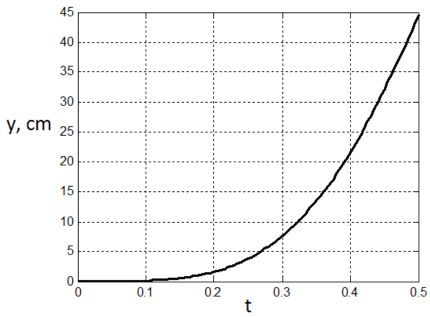

Fig. 6. Horizontal motion due to the tilt command

While the above code can be easy to follow, it is the most basic for this application. The learner can then expand this code to include feedback control to maintain a hovering mode or move steadily in the XYZ space. One of the challenges for the learner, is the availability of numerous quadcopter codes in the public domain. These codes include many additional features and advanced control schemes that overshadow the basics. The learner is usually tempted to dowload one of these codes and run it. Unfortunatly, the learner in this case wouldn't be able to modify the code to incorporate or even deleat features. This is especially true without fully undertanding the mathematical model for all the included features. Trial-and-error starts to take place and much time is wasted without learning how the copter was actually designed. Realizing that the simulator is a tool to validate gained basic knowledge first, needs to be emphasized in teaching. Once the basic concepts are established, the simulator becomes very important as a further development tool. Sometimes, without the simulator more advanced work may not be even possible.

While script code is popular, the same software tool provides "Simulink" which is graphical based. The advantage of Simulink is in visualizing how data is processed. In a block diagram the mathematical equations are processed with clear inputs and outputs to the connected blocks. Figs. 7 and 8 show the Simulink diagram for the same code presented before. The function (fnc) blocks include the algebric terms of the equations only, for simplicity of the diagram. Solving the dynamic equations is achieved with the additional integration terms 1/s outside the function block. Connecting the output terminals of Fig. 7 to the input terminals of Fig. 8 (as aligned) makes a complete program for the quadcopter.

This mode of programming facilitates adding controllers and expanding upon the basic model to include additional features like the drag at high speed and the dynamics of the motors used. The "u1 control" function block in Fig. 7 demonstrates how one can easily incorporate maintained hovering inspite of the tilt of the copter. Fig. 9 shows the code used by the function block. The drop in the vertical effective thrust is determined by the cosine of the roll (gama) and pitch (beta) angles. Observe the labled inputs to the block, "F_{th}", "gama" and "beta". The output is then added to the gravity force value (m*g) and any additional lift command by the user.

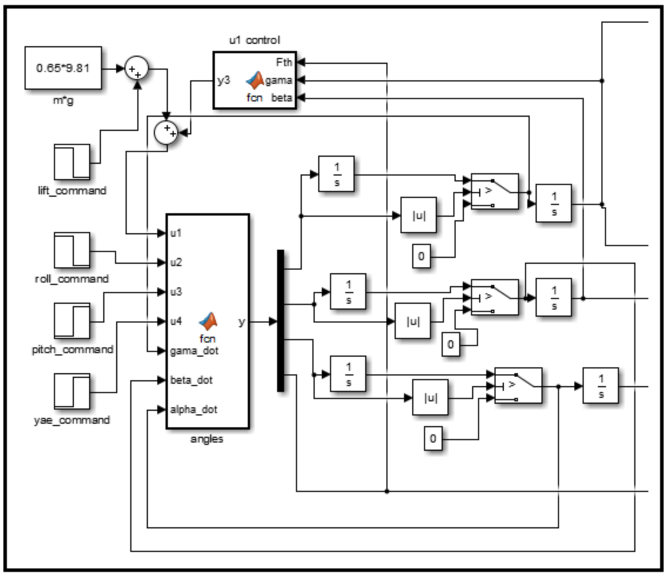

Fig. 7. Simulink code for (3) - (6)

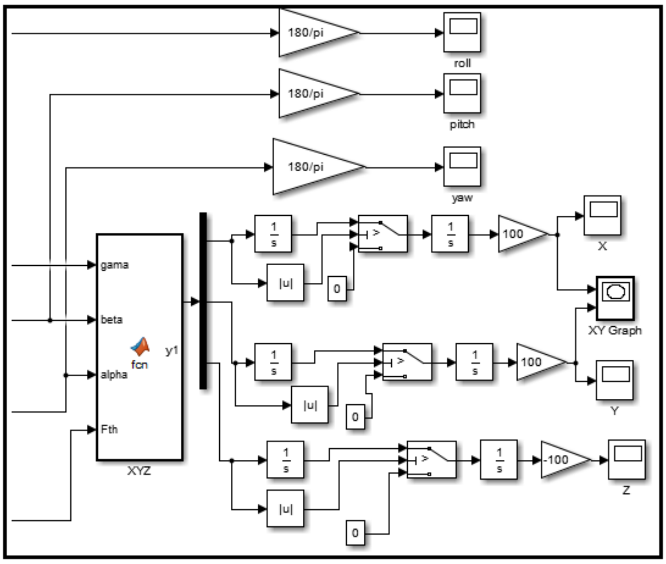

Fig. 8. Simulink code for (7)

```
function y3 = fcn(Fth,gama,beta)
du1=Fth*(1-cos(gama)*cos(beta));
y3 = du1;
```

Fig. 9. Simulink code for hovering control

IV. Teaching Approach

The quadcopter subject is taught as part of a robotics fundamentals course. It is taught in a laboratory environment where computers and other engineering tools are available. The teaching steps taken are as follows:

1) Show the actual quadcopter and use its frame to explain the physical structure and how propellers may rotate.

2) Give a short introduction to mathematical modelling and its significance in solving practical problems. Power_Point presentations may be used to provide documentation and also to facilitate the use of the tablet for inserting notes.

3) Emphasize the significance of computer simulations and give a short demo of the expected results for the quadcopter.

4) Go through the mathematical equations step-by-step while making reference to the implication on the copter's behavior.

5) Present the Matlab script code and explain it in detail. Allow learners time to experiment with it. Respond to questions on observatins of results.

6) Present the Simulink model and explain it in detail. Allow students time to explore the code and make changes.

7) Expand upon the basic Simulink model to include control of altitude as well as XYZ motions. Allow learners time to expand the basic model themselve and demonstrate their work.

8) Demonstrate the actual quadcopter with the remote controller outdoors. Emphasize the propellers' rotation, hovering, tilt and XYZ motions. Subject the copter to additional weight while flying to demonstrate the effect on altitude.

9) Assign learners the task of expanding the basic Matlab code or Simulink diagram to demostrate a certain quadcopter XYZ motion for an application of their choice.

It is worth noting that the focus here is on the teaching approach used to develop the mathematical model, rather than the exact application. This approach can be adopted to introduce other conceptual material with relevant applications.

Conclusions

The presented teaching approach has been used successfully in the classroom. Some distractions during the mathematical modelling part took place, but the motivation to learn remained. The availability of some simulation code at several websites presented a challenge in some cases due to borrowing some of the available code; as a shortcut by the learner. In some instances, the borrowed code wasn't fully understood. Intermediate quizzes proved effective in keeping learners on track. Direct assessment tools (quizzes, exams, assignments) as well as indirect tools (class observations and lab activities) were used to assess the effectiveness of the developed teaching approach.

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