EECS C106B / 206B Robotic Manipulation and Interaction **Spring 2020**

Lecture 27: Dynamics of UAVs & Quadrotors - Examples of Use of UAVs

Scribes: Jessie Mindel, Trevor Voth

27.1 A Brief History of UAVs at Berkeley

A few years ago, a group of professors and graduate students, including Professor Ma, noticed a trend in research on mobile robots, cars, and service vehicles. They wanted to move these two-dimensional findings into the third dimension by way of flight. At the time, Yamaha was making helicopters, and initially selling them to small-time farmers in Japan, who needed a solution for crop dusting and inspection on hilly terrain. Yamaha's solution was the R-50, and later the R-MAX. Ma and his team persuaded Professor Sastry to purchase these helicopters for use in the lab; he then persuaded Yamaha to sell them to his team with the help of Professor Takeo Kanade. The purchase inspired in the team a new perspective on helicopter locomotion: how they might make the entire Yamaha line autonomous.

Research on UAVs at Berkeley began with helicopters (rotorcraft), and later expanded into quadcopters.

27.1.1 Models Berkeley Has Used

- **Ursa Electra (July 2003 - present)**
  Fully autonomous electric helicopter
  First-hand test vehicle for advanced concepts
- **Ursa Major 1 (November 2002)**
  Low-cost, high-payload platform
  Aggressive maneuver, vision-based landing
  Multi-agent scenarios, model-predictive control
- **Ursa Magna 1, 2 (June 1999 - present)**
  Advanced navigation and control algorithm development platform
  Multi-agent scenarios, formation flight, vision-based landing
- **Ursa Maxima (July 2000 - present)**
  High-payload platform for multi-agent scenarios, formation flight, obstacle avoidance

27.1.2 Sensors

At the outset of Berkeley's rotorcraft research, GPS was not yet commercially available. The following sensors were used:

- Laser range finder: Modified light weight scanner with a maximum detection range of 50 m
- Motorized scanner, tilt mount

- For wireless communication:
  - Short range: Wireless LAN
  - Long range (up to 30 mi): Wireless modems
- Inertial navigation sensor CMIGITS-II, containing both an IMU (inertial measurement unit) and GPS with a 100 Hz update rate
- Ground control station: Laptop/PDA and Windows XP/Windows CE
- GPS: Novatel OEM4, with 2 cm StD accuracy and a 20 Hz update rate
- Flight Controller: ADL P3, the Pentium III 700 MHz with QNX RTOS

27.1.3 Shifting to Quadrotors

At the same time as Professor Sastry's group had begun to realize the extent to which helicopters were difficult to control, so too were two other groups coming to a similar realization: Professor Tomlin's lab at Stanford and the founders of DJI. Both found inspiration in history: before Igor Sikorsky invented helicopters but after Leonardo DaVinci attempted to create flying machines, people had been thinking about the notion of a quadrotor. Though it at first seemed that a four rotor design would create more problems than solutions–its likely fragile and also dangerous rotors might bump into things–both groups persisted. Tomlin's lab was the first university group to popularize quadrotors through their work on STARMAC (The Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control). At the same time, the founders of DJI thought to commercialize the idea, and DJI is now the booming success we know it to be.

27.2 How Helicopters Work

A helicopter (referred to in lecture as a rotor or rotorcraft) has four main rotors:

- The **main rotor** provides lift.
- As the main rotor spins, it generates torque. To keep the helicopter from spinning in the opposite direction to that in which the main rotor moves, a **tail rotor** is needed.
- Below the main rotor, there are two other blades that form the **swashplate**. These are used to adjust the angle of attack, or the angle of the blades on the main rotor. By adjusting this angle, one can vary the amount of lift, or create not exclusively vertical but sideways force from the main rotor.

Helicopters are substantially more complex than quadrotors, as previously discussed.

27.3 Examples of Use of UAVs

27.3.1 Pursuit-Evasion Game Experiment

Goal: Can UAVs help unmanned ground vehicles coordinate?

How: The group purchased a number of Pioneer robots, some of which pursued others, and some of which evaded the pursuers. A UAV would fly above the evader and help the pursuers pursue it. All robots build a probabilistic road map by investigating a cone in each robot's vision of where the evader is, and then plan to reach it, over four rounds of search.

27.3.2 Vision-based Landing of an Unmanned Air Vehicle

Goal: Using computer vision, land a UAV on not only a stationary platform, but on a moving one (emulated using a Stewart platform).

How: The computer vision system used corner features, stereo vision, and motion estimation, working to avoid camera mount vibration (or mitigate its effects). Boeing made available to Berkeley the flight control system used on all Boeing military aircraft for use in this project. Using vision, the system tries to estimate where the deck is; one challenge was that when the deck consistently moved, it was difficult to finally touch down, and the helicopter might be stuck hovering above the platform for a while. All vision work done is motivated by the theory we learned this semester from Professor Ma.

27.3.3 3D Terrain from Parallax

Goal: Reconstruct a scene using aerial photography performed by UAVs.

How: Specifically using Boeing's R-22 and Open Control Platform (or OCP, Boeing's flight operating system), synthetic video was generated as the helicopter flew in spirals over the surface of Victorville, again using the same principles of multi-view geometry that we have studied in this class. The system was sufficiently robust and fast to detect boulders, the landscape of the desert, etc., and determine where to land.

27.3.4 Conflict Detection and Resolution

Goal: Prevent collisions when two UAVs are about to collide head-on.

How: Two planes were programmed to collide head on, but an MPC controller was developed to prevent such a collision. The two planes at first awkwardly rotate when they would have otherwise crashed, unsure of how to resolve the conflict, but eventually rotate far enough to cycle around and move in opposite directions, avoiding the collision by making somewhat of a circle around what would have otherwise been the crash site.

27.3.5 Autonomous Coordinated Flight

Goal: Fly large numbers of helicopters in formation with minimal space between them. Ease the load of pilots flying in formation in low-visibility settings by creating an unmanned alternative for this difficult maneuver.

How: The team was required to have manual takeover pilots for safety. Because only two pilots were available, the team opted to have two real UAVs, and seven added virtually to the scene. UAVs assembled in a platooning formation, and communicated neighbor-to-neighbor to see if the work could be performed without global communication. As desired, UAVs were able to fly extremely close to each other.

27.3.6 Obstacle Avoidance Using Model Predictive Control and a Laser Scanner

Goal: Navigate a complex 3D environment (such as an urban environment) in real time without getting stuck.

How: This project introduces NMPC, or nonlinear model-predictive control. The map is built using laser scanners and cameras with tilt mounts. Six buildings were modeled as blue pop-up tents iat the Richmond field station to simulate an urban canyon.

27.3.7 New Platforms

Given the difficulty of controlling a helicopter, the group introduced new UAV platforms, three of which we discuss here.

27.3.7.1 BEAR Coaxial UAVs

By using two rotors spinning in opposite directions, one no longer needs to include a tail on a rotorcraft. Such a rotorcraft is called a coaxial UAV. Berkeley began building these, but during a demo, one of the parts broke because of the large amount of strain produced by the coupling between the coaxial parts. As such, further work on this model was not pursued.

27.3.7.2 Tankopter

A helicopter with treads for transitioning between ground and air travel; creates micro-maneuver capabilities.

27.3.7.3 Smart Bird

A backpack-sized, fixed wing UAV (not a rotorcraft). It can be easily disassembled and reassembled for storage in a backpack. One motor connected to wires adjusts the flaps. Rather than using a tail, it uses wingtips for the roll moment and pitching moments. It was demoed at the Richmond field station with great aerial views of the surrounding area.

27.3.8 NEST

A sensor field: magnetometers, passive infrared motion detection sensors. Multi-target tracking allows the system to pick up different activity, such as people walking through the sensor field. 557 nodes were deployed to form the network. The system was tested on a pursuit-evasion game (as in 27.3.1) with humans evading virtual agents; virtual agents were able to find and pursue the humans using the sensor data.

27.4 Quadrotor Dynamics

27.4.1 Euler's Equations

The traditional matrix form for Euler's Equations for rigid body dynamics using a rotating reference frame: (see Figure 27.1 for reference)

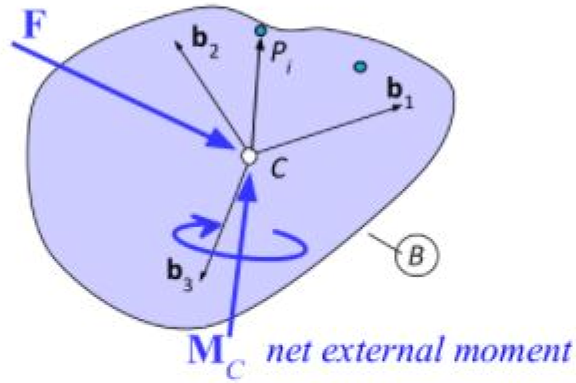

Figure 27.1: Euler Equation Reference

$$\begin{bmatrix} I_{11} & 0 & 0 \\ 0 & I_{12} & 0 \\ 0 & 0 & I_{13} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} + \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \begin{bmatrix} I_{11} & 0 & 0 \\ 0 & I_{22} & 0 \\ 0 & 0 & I_{33} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} C_{C,1} \\ C_{C,2} \\ C_{C,3} \end{bmatrix}$$

27.4.2 Application to Quadrotors

From Figure 27.2, we can gather that resulting forces are:

$$F = F_1 + F_2 + F_3 + F_4 - mga_3$$

and, given that motors 1 and 3 rotate clockwise while motors 2 and 4 rotate counterclockwise, the resulting sum of moments are:

$$M = (r_1 \times F_1 + r_2 \times F_2 + r_3 \times F_3 + r_4 \times F_4) + (M_1 + M_2 + M_3 + M_4)$$

where $F_i = k_F(\omega_i)^2$ and $M_i = k_M(\omega_i)^2$.

Let $\gamma = \frac{M_i}{F_i}$:

$$I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} L(F_2 - F_4) \\ L(F_2 - F_4) \\ M_1 - M_2 + M_3 - M_4 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & L & 0 & -L \\ -L & 0 & L & 0 \\ \gamma & -\gamma & \gamma & -\gamma \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

We can see that $u_2 = \begin{bmatrix} 0 & L & 0 & -L \\ -L & 0 & L & 0 \\ \gamma & -\gamma & \gamma & -\gamma \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$.

Thus it follows that $u = \begin{bmatrix} u_1 \\ \\ u_2 \end{bmatrix} = \begin{bmatrix} thrust \\ momentaboutx \\ momentabouty \\ momentaboutz \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & L & 0 & -L \\ -L & 0 & L & 0 \\ \gamma & -\gamma & \gamma & -\gamma \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$

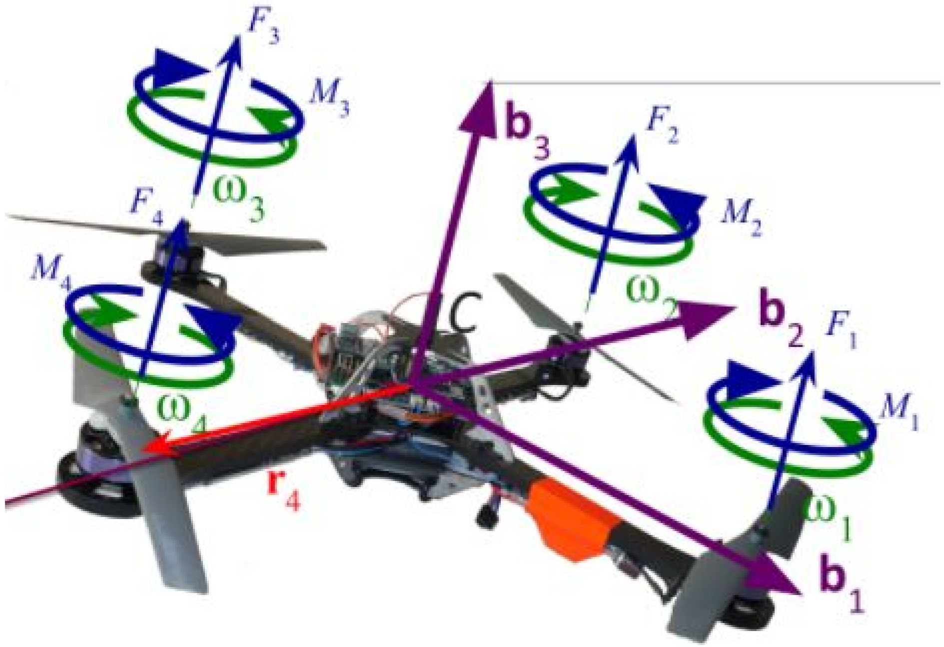

Figure 27.2: Quadrotor Dynamics Visualized

We now have representation for the inputs required for our quadrotor!

27.5 Planning with Dynamics

To control a quadrotor, we can use exactly the same work we did on feedback linearization earlier in the semester. This system is nonholonomic. When we linearize the system on $SE(3)$, we get a system with 12 state variables and 4 state inputs: 6 state variables from $\log(R)$ (since the log of a hatted twist retrieves the twist), and 6 state variables from $\log(\dot{R})$. Even with only 4 inputs to its 12 state variables, this system can be feedback linearized.

Loianno, Brunner, Kumar, and McGrath's work at UPenn demonstrate such a controller in action: a UAV is able to navigate through 45 and 90 degree slits, with trajectory plans consisting of going sideways through these slits. The algorithm used is a modified version of A*.

27.6 On Developing the Future

On an inspiring closing note, Professor Sastry explained that Final projects often look rather makeshift. In roughly his words: as you're working on it, tech looks like it's held together by failing wax and Scotch tape. At the time we were doing this, some of it looked really far-fetched. At the time, we were really just trying to not get the thing to crash. But don't underestimate what you're doing, because what you start doing becomes tomorrow's future. Today, you wouldn't think twice about landing UAVs. Amazon will have UAVs deliver packages, UAVs will fight forest fires, and UAVs might be used for surveillance.