### Feedback Control System for Drones

The goal of this discourse is to introduce an example of a feedback control design that provides the accurate navigation and robust stabilization of Line-of-Sight (LOS) beam control of a laser that is directed to a ground target. This design example also allows for stabilization of meta-stable air vehicles.

SpaceX has introduced maneuvering and stabilization of a low velocity rocket which does not rely on aerodynamic forces for stabilization. The meta-stable condition of a slow-moving rocket is due to being top-heavy with a small exit nozzle cross-sectional area. The small cross-sectional area at the thrust applied exit nozzle is applied to the slender rocket body which is meta-stable due to deviations of the thrust direction vector from the high center-of-mass.

Rockets and other drone type air vehicles with sensor and interrogator payloads located at the top of the airframe benefit from active stabilization of Thrust Vector Control (TVC). In this configuration the sensors and interrogators are far away from the turbulent vibrations of the propulsion thrusters and have a peering capability above/over objects advantage. TVC provides for quick responsive attitude corrections due to disturbance forces that can easily set a slender air vehicle or slow-moving rocket into a toppling over condition.

This discourse presents systems solutions rather than mathematical derivations behind digital filters, lead-lag compensators, control feedback laws, and nonlinear limit functions. My intention is to show a system architecture for precision guidance and control while leaving out the details required for implementation and application.

Precision control under adverse conditions is desired for stabilization of camera jitter and the steady-cam gimbals which are currently in use. The typical configuration places the camera onto a gimbal platform but an alternative configuration could be the fixing the camera to the air vehicle platform and using a Beam Steering Mirror (BSM) to stabilize the scene to the camera. The mass moment of inertia of a BSM is lower than that of a camera mounted to a gimbal torquer and this would provide for greater frequency response bandwidth image stabilization.

The feedback control design I created incorporates a nested-loop feedback controller with an attitude-hold or steady-orientation control law. The outer feedback loop is for guidance control and the inner loop is for stabilization. The angular rate sensors are configured for the higher bandwidth inner stabilization loop while the attitude and heading sensors are configured for the lower bandwidth outer guidance loop. The feedback control diagram shown below describes this nested-loop feedback controller configuration.
The input commands are generated from the operator manipulating gimbals for throttle, roll, pitch, and yaw control of the air vehicle. The 50 Hz sample rate Pulse-Width Modulator (PWM) encoded signals are converted to a sampled data signal through the PWM Demodulator unit. The sampled digital signals are then processed through a Low-Pass Filter (LPF) and a derivative function that produces a command signal rate. The LPF produces a lag to the command signal with respect to the derivative function. Alternatively, the derivative command signal is advanced with respect to the command signal amplitude which is desirable. Both the command signal amplitude and command signal rates enter the feedback control loop which compares the feedback sensor signals to produce an error signal. The error signal is then amplified followed by being processed with lead-lag compensators. The gains and lead-lag compensator variables provide tuning of the controller to the air vehicle dynamics. The output of the rate lead-lag compensator enters an integrator prior to being summed with the output of the orientation angle (x_error) lead-lag compensator. The signal integrator converts the rate to displacement or angular position. The integrator can be replaced with a LPF to prevent the integration of the DC-component which would eventually reach the clipping rail voltage of the processor. The output of the signal integrator can be balanced with the gain matrix settings to compensate sensitivity of angular position to rate feedback control response dynamics.

The error signal amplitude and integrated error signal rate are summed together at the output of the lead-lag compensators and the resultant signal enters the gain-offset adjustment function. The gain and offset function is to match the sensitivity of the closed-loop feedback controller output to the range of the PWM interface to the servo actuators. The gain and offset parameters are adjusted to each of the servos which control the thrust and direction of the air vehicle. The gain-offset adjustment function also distributes the output signal to the various servo actuators which drive the associated aerodynamic, thrust, thrust directors and other body motion controls. The output signals from the gain-offset adjustment function are passed through a bank of LPFs and PWM modulators since typical servos are configured to read a PWM input signal. The flight surface controls, thrust controllers, and thrust vector
gimbals set the airframe body into rectilinear and angular motion which is detected by the attitude rate sensors, attitude/heading sensors, and additionally, other sensors such as accelerometers and altimeter.

Disturbance sensing can be accomplished by placing strain gage sensors on a linkage arm to one of the aerodynamic flight control surfaces. If disturbances are detected prior to airframe body response then feedback control can be more proactive than reactive given this advanced notice sensing method. This would be important for a wavelet-based feedback control system which is sensitive to a spectrum energy disturbance and would adjust the gain vectors and phase control parameters in order to maintain stability in a high disturbance environment.

The attitude rate sensor output is passed through a High Pass Filter (HPF) which also adjusts the sensitivity level to match the input command rate. The HPF removes the DC-offset signal of the gyro so that gyro bias drift is no longer an error signal of concern. Instead, the DC-component is measured by the attitude/heading sensor which also has sensitivity level adjustment to match the input command amplitude. The LPF preserves the direct measurement of air vehicle tip-tilt angles as well as heading angle with minimal noise due to the low frequency setting of the filter. The outputs of the feedback signal LPF and HPF enter a quaternion algorithm which integrates the measured angular rates and converts them back to Euler attitude angles only when the HPF is bypassed. In this configuration the gyro bias drift can be monitored with respect to the attitude sensor and heading sensor signals.

The quaternion algorithm performs attitude determination by integrating the gyro rates and initializing the quaternions with Euler angles. The Euler angles can be updated using the attitude and heading sensors to re-initialize the quaternions. The quaternion algorithm produces a transformation matrix and from this transformation matrix the Euler angles for attitude and heading can be determined when the HPF is bypassed. The quaternion initialization matrix can then be invoked to periodically update the quaternion vectors with a true measurement of roll, pitch and yaw. The output of the quaternion algorithm sends feedback angles and feedback angular rate signals to another gain and offset adjustment function in order to provide amplitude level matching of the quaternion algorithm output to the input command (set-point) level. The output of the gain and offset function feeds back the sensor signals at the summing junction to the input of the controller for comparison to the command signal or set-point reference signal.

A bare metal Real-Time Operating System (RTOS) loaded onto a floating-point unit Microcontroller Unit (MCU) is recommended over a Linux or Windows based Operating System (OS) due to the interrupts of Linux or Windows OS that impact real-time GNC Input/Output (I/O) processing. A RTOS is a low-level OS with minimal disturbance interrupts to real-time operations. Real-time processing can be delayed by operating system memory management, status checking and housekeeping operations. OS interrupts create undesirable delays in real-time processing, streaming and operations. An FGPA, on the other hand, presents no interrupts since there is no bit clock and is typically used for image processing repetition across pixel arrays.

An example of interrupts impacting real-time processing is the TCP/IP protocol which can hold up an entire process waiting on the re-sending of a data packet therefore a bare-metal RTOS is recommended for reliable GNC flight and auto-pilot control. Typical interface protocols to the MCU are analog signal, UART, SPI, I2C, PWM encoding, PWM decoding, USB, Ethernet, Wireless/Bluetooth, RS-232, RS-485 as the MCU is primarily performing high-speed numerical processing I/O with minimal data storage.
Detail of actuator/sensor interactions with the air vehicle are shown in the figure below.

The servos, guidance effectors, throttle controllers, and sensors are mounted to the air vehicle for motion detection, guidance control, and stabilization. Flight surface control, thrust control, and thrust vector gimbal software-to-hardware interface functions are summed to produce an applied moment to the air vehicle. The inertia tensor matrix defines the applied angular accelerations to the body. The
angular accelerations define the control authority. High control authority leads to de-stabilization or instability producing too high correction rates. Low control authority leads to poor maneuverability and slow responsiveness. In this case a disturbance can create instability due to the long-time lag for correction.

The angular acceleration is then integrated to produce and body rate and again integrated to produce a body angle. The roll-pitch-yaw rates are measured with a three-axis gyro and the attitude and heading angles are measured with an inclinometer sensor and magnetometer sensor. The inclinometer and magnetometer vector signals are then summed and passed to a LPF while the gyro signals are passed to a HPF where under certain conditions the HPF can be bypassed. A bypassed HPF provides for DC-coupled attitude determination from the integrated quaternion rates (or integrated rate gyro signals) instead of air vehicle vibration measurement when the HPF is implemented.

The highest performance gyros with the lowest bias-drift error are mass-spinning inertial gyros as found on the Hubble Space Telescope followed by ring-laser gyros, sagnac based fiber-optic gyros, and Micro-Electro-Mechanical Systems (MEMS) gyros. MEMS gyros have significant bias-drift error which impacts the navigation accuracy of air vehicles or any other type of vehicle. The Global Positioning System (GPS) cannot provide attitude determination for slow moving and slow rotating vehicles. GPS re-synching to satellites can create timing errors where the time can either advance (jump forward) or retard (jump backward) and produce a transient glitch or dead-band interval in the streamed data. GPS presents large error in altitude determination as the satellite triangulation geometry presents an ellipsoidal error with the largest error along the vertical axis. GPS provides more accurate measurements along the plane of earth’s surface, so GPS is not recommended for attitude determination or altitude determination of drone air vehicles and other sensing methods should be considered.

A method to cancel common-mode drift error of MEMS gyros is to configure them back-to-back so that by subtracting the outputs the result will be the average of two gyro signals along with cancellation or nulling of the common-mode thermal-electrical drift. Since MEMS gyros are an inexpensive technology solution then stacking multiple gyros for three-axis drift error cancellation is a viable solution to precision navigation. Gyros are also used in gimbal bearing platforms for steady-cam applications.

Inclinometers are typically MEMS based or electrolytic-fluid based. The MEMS based inclinometers use accelerometers to measure the tip-tilt (or roll-pitch) angle. MEMS accelerometers are noisy and therefore not as reliable for measuring small angles as compared to electrolytic-fluid based tilt sensors. The accuracy, precision and resolution of angle measurement becomes critical for stabilization of meta-stable inverted pendulum (or top-heavy) air vehicles.

A magnetometer is a reliable heading sensor that detects the earth’s magnetic field flux similar to that of a magnetic compass needle. A single-axis pivoting compass or magnetometer presents an error when a tip-tilt (or roll-pitch) angle is introduced. Since the magnetometer is mounted to the air vehicle then the tip-tilt angle needs be measured in order to correct the error in magnetometer reading. A tip-tilt compensation algorithm that takes into account an Euler rotation matrix sequence can be used to correct the magnetometer heading readings.

A magnetometer is also sensitive to locally generated magnetic fields such as those generated by high-voltage wires. In this case the magnetometer would track the gradient of the local magnetic field which would interfere with the earth’s magnetic field and be in conflict with heading determination based on
the gyros. An array of multiple magnetometers across the airframe can be used to detect the gradient of the magnetic field thus identifying the presence of a local magnetic field anomaly. Either comparing the magnetometer to gyro based heading estimation or comparing the magnetometer to surrounding magnetometers to measure a magnetic field gradient will reduce the error in inertial based heading determination.

One implementation of a LPF is shown in the figure below.

There are other implementations of low-pass filter such as the finite-difference equation method, bilinear transform method, and the Fourier transform method. The bilinear transform method relates the discrete z-transform variable to the continuous system Laplace \((s=j\omega)\) variable. The advantage of the state-space integration method is data oversampling can be easily obtained within the integration loop.

The input signal forcing function \(x_i(t)\) is sampled at a 50 Hz sampling rate and enters two z-transform delay lines. The resultant input signal to the filter loop is \(x_i = x_i(t) + 2x_i(t-\Delta t) + x_i(t-2\Delta t)\) which enters the feedback loop. The gain matrix can be set to unity for an ideal filter with tuning parameters \(\omega_n\) and \(\zeta\). Critical damping is when \(\zeta = 1/\sqrt{2}\). This low-pass digital filter converges well with an inner loop cycle at x10 with respect to each update where \(\Delta t = 10^4 dt = 1/\text{smpl_rate}\). In this case 2x oversampling would occur at every 5th loop iteration of the signal integration function. Since this a closed-loop feedback architecture
for a filter function then the feedback signal to the summing junction can also include sensor signals such as gyro/inclinometer/magnetometer outputs. The state-space integration LPF would then perform an integrated or combined function that includes the feedback sensors into the closed-loop feedback control function of the filter.

The feedback control system presented in this discourse is intended to stimulate ideas for new theories, architectures and applications. A wavelet-based (or digital wave energy detection filter bank array) feedback controller which uses Eigen values instead of state-variables for feedback. This solution can track the nonlinearities of the dynamic system. Wavelet based feedback control will be presented in a subsequent topic.

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