AVIONICS SYSTEM FOR A SMALL UNMANNED HELICOPTER PERFORMING AGRESSIVE MANEUVERS

V. Gavrilets[1], A. Shterenberg[2], M. A. Dahleh[3], E. Feron[4], M.I.T., Cambridge, MA

Abstract: **An Xcell-60 5 ft rotor diameter hobby helicopter was instrumented to perform autonomous aggressive maneuvers. Avionics system, state estimator design, and vibration isolation are presented in detail. Analysis of helicopter dynamics based on flight data is given.**

Introduction

Recently there has been considerable interest in applications of small unmanned helicopters. Most of research was concentrated on achieving greater autonomy, for example using imaging sensors to perform a navigation task (International Aerial Robotics Competition, research at Carnegie Mellon Robotics Institute). One interesting feature of small-size unmanned helicopters is their outstanding maneuverability, because they are not constrained by human presence onboard. A small hobby helicopter with vibration mounted film camera was used to create a highly agile falcon-eye video for a National Geographic TV documentary, aired in January 2000. During the videotake a 5 ft rotor diameter helicopter was manually flown between skyscrapers in Bronx. Wide maneuver envelope and hovering capability of small helicopters can potentially be used in urban warfare.

To make aggressive maneuvering safer and decrease overarching dependence on skills of a pilot, it is necessary to design a feedback control system with adequate closed loop bandwidth. We are preparing a demonstration of fully autonomous flight featuring aggressive maneuvers, including split-S and longitudinal loop. This paper describes an avionics system we implemented to achieve high-bandwidth feedback control, robust to modeling errors and gusts. Vibration isolation with proper frequency characteristics is essential for high-g flight of a rotorcraft. We summarize our successful vibration mount design in the paper.

Description of a test vehicle

Our test vehicle, shown in Figure 1, is an alcohol-powered Xcell-60 hobby helicopter.

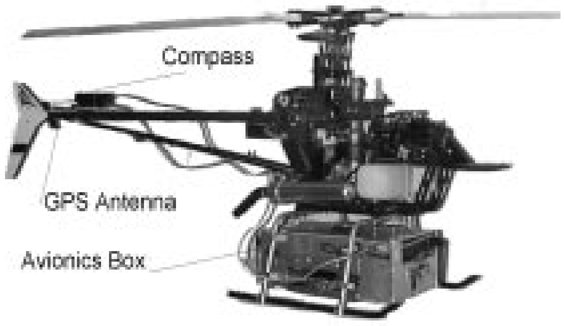

Figure 1. M.I.T. Xcell-60 with avionics system

It has a two-blade teetering rotor augmented with Bell-Hiller stabilizing bar. Rotor diameter is 5 ft. Gross takeoff weight (with 7 lbs of avionics added to the airframe) is 18 lbs. A well-trained RC pilot has performed high-speed 2 g turns, full longitudinal loops, and high-rate stall turns with the data acquisition payload. Rotor speed range is 1500-1700 RPM. An electronic governor maintains commanded rotor speed by adjusting throttle commands. A hobby gyro provides proportional negative feedback of measured yaw rate to tail rotor pitch, thereby augmenting yaw rate damping. The

---

[1] Ph. D. candidate, Department of Aeronautics and Astronautics, gavrick@mit.edu
[2] M.S. candidate, Department of Electrical Engineering, alsh@mit.edu
[3] Professor of Electrical Engineering, dahleh@lids.mit.edu
[4] Associate Professor of Aeronautics and Astronautics, feron@mit.edu. Corresponding author.

other actuators are lateral and longitudinal cyclic pitch, and collective pitch of the main rotor blades.

The helicopter was equipped with a data acquisition system. All vibration sensitive equipment is contained in the avionics box (Figure 2) mounted on elastomeric isolators, which were chosen and located in such a way that rotational and translational vibration inputs are well attenuated. Vibration issues are described later in detail.

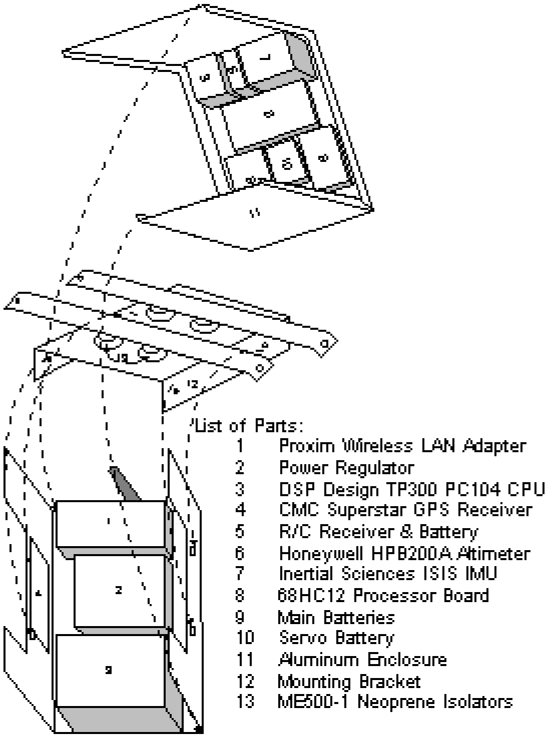

Figure 2. Vibration-isolated avionics assembly

Helicopter dynamics and state estimation

The flight sensors were chosen such that all relevant state vector elements can be estimated with reasonable bandwidth of the observer (10-15 rad/sec depending on the state). Some full state feedback design methods, like LQR, are well known to provide excellent robustness to modeling errors, with 60 degrees phase margin and ½ to infinity gain margin in any actuator path. This is essential, since it is rather difficult to model or identify rotorcraft dynamics accurately, especially in fast forward flight. Full state feedback also suppresses undesirable cross-axis responses much better than independent SISO feedback loops, given similar closed loop bandwidth. In addition, availability of full state estimate makes system identification problem significantly easier. Thus our goal is to select the set of states such that dynamics (including cross-axis responses!) is adequately represented up to a certain bandwidth. The rest of the dynamics, like servo response, can then be modeled by transfer functions. These additional lags must be accounted for when selecting a closed loop bandwidth of the system.

Linearized rigid-body dynamics for most helicopters can be adequately described by 8 states, namely 3 body axis velocities, 3 inertial angular rates, and Euler roll and pitch attitude angles [1]. Occasionally state vector is augmented with two states corresponding to the Bell-Hiller stabilizer bar dynamics. The stabilizer bar improves damping of unstable lateral and longitudinal phugoid modes at the expense of lagged response to cyclic inputs. Authors of [2] estimated that stabilizer bar on a much larger Yamaha R-50 helicopter contributes a lag with time constant of roughly 5 rotor revolutions to lateral and longitudinal pitch cyclic actuation. The rotor speed at hover on R-50 is 850 RPM [2], which resulted in the estimated time constant of 0.38 sec, or roughly 2.5 rad/sec cutoff frequency. This is rather close to rigid body modes of the helicopter, and as a result a model that couples flybar and angular rate states was used in [2] for system identification. The Xcell 60 rotor speed is roughly two times higher, which leads to the estimated lag of approximately 0.2 sec. This estimate is well supported by flight data. We applied a first order filter with time constant of 0.2 sec and gain of 20 (deg/sec)/deg to longitudinal cyclic pitch. A filter with the same time constant and a gain of 30 (deg/sec)/deg was applied to lateral cyclic pitch. Higher gain in the roll channel is due to lower roll inertia. The results are compared with pitch and roll rate time histories in Figure 3. During this segment the pilot performed a 2-g turn at 10 m/sec forward speed. Time histories of roll and pitch Euler angles are given for completeness.

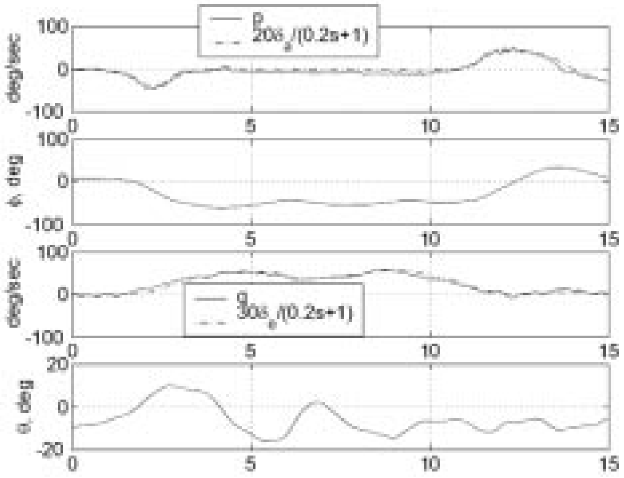

Figure 3. Angular rate response to cyclic commands

We feel that it is adequate for flight control design purposes to model the effect of the flybar by two first order lags, neglecting coupling between flybar states and pitch and roll angular rates. In fact, because of relatively stiff rotor blades R/C pilots perceive cyclic inputs on such a helicopter as a slightly lagged rate control system, which is well illustrated in Figure 3. This actuation lag has an implication that crossover frequency in pitch or roll attitude or rate tracking loop can not be pushed beyond roughly 2 rad/sec in order to retain adequate phase margin. The advantage of this modeling approach is that the flybar states do not have to be measured for feedback. Note that human pilots can perform exceptionally agile maneuvers without knowing flybar position.

The yaw rate gyro is set to provide proportional feedback to tail rotor pitch, therefore it does not require additional states for modeling. For modeling purposes the feedback gain setting of the gyro can be easily measured by swinging a suspended gyro, and measuring the angular deflection of a servo. Maximum servo deflection is proportional to the maximum angular rate, which is a product of maximum angular deflection of a swinging pendulum and its natural frequency.

In addition to the aforementioned eight states, we would like to estimate heading and 3D inertial position vector for a fully autonomous flight. Inertial measurement unit, consisting of three gyros and three accelerometers, provides high-bandwidth information about state vector. The main error source in the integration of rotational and translational inertial navigation equations are gyro biases. Therefore we implemented a 13-state extended Kalman filter (EKF). The EKF state vector includes three inertial positions, three inertial velocities resolved in body axis, four elements of a quaternion representation of attitude, and three rate gyro biases. Note that the gyro biases drift over time, and this drift turns out to be significant for our duration of flight (15 minutes). It is highly beneficial to include gyro biases as states, since then attitude estimate can be derived by dead-reckoning during short GPS outages. On the other hand, accelerometer biases are relatively small (within 10 mg), and they introduce small errors to attitude estimate. The state vector is propagated at 25 Hz with 4th order Runge-Kutta algorithm (IMU is sampled at 100 Hz). Once per second measurement updates are available from GPS (3D inertial position and velocity), barometric altimeter, and magnetic compass. Roll and pitch rate gyro biases are well observable in horizontal GPS position and velocity measurements. Yaw rate bias can be compensated for by the compass magnetic heading measurement. GPS vertical velocity, altitude, and pressure altitude are used essentially to compensate for vertical accelerometer bias. Note that this state estimator design is quite robust to short GPS outages. After convergence of gyro bias estimate errors to 0.01 deg/sec, helicopter attitude can be estimated to within 1 deg for around 1 minute, which provides plenty of time for the safety pilot to switch to manual control. In addition, barometric altimeter will keep up-to-date altitude reference.

Note that the velocities are measured w.r.t. inertial frame, and not w.r.t. air. Therefore, steady winds and gusts have to be treated as disturbances by the control system. Since our goal is demonstration of aggressive maneuvers, we impose a limit of 10 knot winds for flight operations.

Next section provides more detailed description of flight sensors, as well as other elements of our avionics system – computers and servos.

Avionics description

Safety, high bandwidth requirement for the flight control system, and adequate sensor information were key factors in designing the avionics package. The appendix contains the block diagram of the electronic components and their interconnections.

Computing and Telemetry

Most of the processing is done in the Central Processing Unit (CPU). The CPU is a 266 MHz PC104 board with 32 MB of RAM and 16 MB of permanent flash RAM. Input and output channels of the CPU include 4 serial ports, 4 A/D channels, ethernet and parallel port, most of which are used by the sensors and actuators. The CPU runs the real time operating system QNX.

In order to facilitate helicopter recovery in case of CPU or main battery failure, a separate microprocessor powered from a different power source handles the task of driving the servo actuators with pulsewidth modulation (PWM) waveforms. The device is labeled Micro Controller Unit (MCU) in the block diagram. During normal automated control operation, the MCU receives serial commands from the CPU and converts them to five PWM signals. In the datalogging mode, the MCU digitizes R/C pilot's commands coming from the receiver and passes them through to the servos while simultaneously sending the commands to the CPU via the serial link. In the event of the main computer failure, the pilot has to flip a switch on the transmitter, which directs the MCU to pass PWM signals from the receiver directly to the servos. The MCU is implemented on a Motorola 68HC12 prototyping board. In addition to its main function, the MCU also has RF filtering electronics for the receiver commands and optical isolation circuitry to isolate the servo bus from the rest of the electronics.

The CPU communicates with the ground station via a wireless LAN telemetry system. While wireless LAN offers the benefit of high throughput, its poor reliability and timing prompted the decision to leave the telemetry system out of safety critical loops. Wireless LAN link is used only for monitoring and data logging. Having an ethernet link also proved to be an extremely valuable debugging tool. Proxim RangeLAN2 ethernet adapter was chosen for the task. The adapter offers bandwidth as high as 1.6 Mbits/s for large packets. Since it connects to an existing ethernet controller, Proxim did not require writing any QNX drivers.

Sensors

The Inertial Measurement Unit (IMU) provides the bulk of sensor information to the CPU. The unit contains three gyroscopes and three accelerometers. The outputs of the sensors are temperature compensated internally. The IMU was chosen for its accuracy over extended input range and light weight. The unit weighs 250 grams. After 10 minute preflight warm-up, the biases of the gyros drift on average by .03 degrees/sec and the biases of the accelerometers drift by 5 mg during 15 minute flight. The full scale of the gyros was chosen at +/-300 deg/sec to enable high-rate maneuvers around any axis. The IMU provides 100 Hz updates of the rates and specific forces through the 115.2 Kbit/sec serial port. The device is manufactured by Inertial Sciences Inc.

The Superstar GPS receiver from Canadian Marconi provides 1 Hz updates of the inertial position and velocity. Since the practice of scrambling GPS signal for civilian users, known as Selective Availability, was discontinued on May 1 2000, short term relative navigation with GPS provides horizontal accuracy on the order of several meters. Duration of flight for our helicopter is limited to 15 minutes by the amount of fuel it carries. The main source of GPS errors in the absence of selective availability is ionospheric delay, and since the path traveled by a signal from a satellite to the helicopter does not change significantly in 15 minutes, the errors are small. Blending GPS and IMU measurements, as well as other sensors in the EKF further improves navigation accuracy. Therefore we do not have to use differential GPS for a fully autonomous 15 minute flight.

Triaxial magnetoresistive sensor HMC2003 from Honeywell is used to measure three components of Earth magnetic field in projection to body axis. It is mounted on horizontal fin, far away from the engine and avionics box. The compass requires scale factor and bias calibration to compensate for magnetic fields induced by helicopter-mounted components. In addition the EKF estimates of roll and pitch angles are used to resolve magnetic field in local North-East plane. The resolution of the magnetic field measurement on a 12 bit A/D converter is 1 milliGauss, which approximately corresponds to 0.3 degrees in a 200 milliGauss Earth magnetic field. Although the EKF heading updates are made only once a second, the analog readings are sampled at 20 Hz, and passed through first order analog filter to avoid aliasing.

HPB200A barometric altimeter from Honeywell is used to provide additional altitude information to GPS measurement. This is an absolute pressure sensor with the range 0-17 psi. Sensor resolution is 0.001 psi, which is roughly 2 ft, and the reading is quite stable. The altimeter is sampled 10 times a second. The pressure change due to induced velocity from the rotor turns out to be small. According to momentum theory, dynamic pressure change due to induced velocity is equal to T/4/A, where T is thrust, and A is rotor disc area. For our helicopter with 18 lbs gross weight and 5 ft rotor diameter this value is 0.0016 psi, which results in roughly 3 ft altitude error. A wind of 10 knots would have the same effect. Effects of gusts and thrust variations due to collective changes will be on the same order, and these higher-frequency errors are low-pass filtered by the EKF.

Actuators

High bandwidth servos, especially for the tail rotor pitch, are essential to achieve closed loop bandwidth adequate for aggressive maneuvers, without compromising stability. Fast hobby servos were chosen for all channels except throttle, where the response is dominated by the slow time constant of the engine. JRDS8417 servos were used. Their slew rate is 600 degrees/second, which translates to roughly 7 Hz bandwidth (frequency at which 90 degrees phase lag occurs).

Vibration isolation and prefiltering

Vibration environment on a small helicopter is rather complex. The main source of large-amplitude high-frequency vibration inputs is the main rotor, spinning roughly at 26-27 Hz. The harmonics are 1 per revolution, 2 per revolution (blade passage frequency near tail rotor), engine frequency (around 160 Hz), and tail rotor frequency (around 115 Hz). These inputs also have sidebands, which excite lateral and vertical first bending modes of the tailboom (20 Hz). These inputs combined have amplitudes on the order of 40 deg/sec and 1 g in all axes, and have to be attenuated to make use of gyro and accelerometer data. Passive vibration isolation was designed for the avionics box weighing 7 lbs. The resulting rotational cutoff frequencies are in the range of 7-9 Hz, and translational frequencies of 11 Hz in horizontal plane, and 13 Hz in vertical direction. The cutoff frequencies have to be low enough to provide sufficient attenuation of high-frequency vibration sources, at the same time the suspension system should be sufficiently stiff to sustain high-g maneuvers without bottoming out. Low rotational cutoff frequencies were achieved by close spacing of isolators inside the avionics box (see Figure 2). The isolators were located in the corners of a rectangle, the geometric center of which coincides with the center of gravity of the isolated assembly. This decouples rotational and translational modes [4]. Neoprene isolators (ME500-1 from Barry Controls) were chosen primarily for availability in stock and low cost ($10 a piece). Neoprene has damping ratio of 0.05, which results in fast decay of transmissibility function, but also has 10:1 amplification factor at resonance. The suspended assembly resonances get excited by broadband vibration inputs. Since these resonant frequencies are significantly faster than helicopter rigid-body dynamics, we used digital notch filters to remove these modes. A higher damping material, like Barry-LT compound, can also be used.

The suspension assembly attenuates high-frequency vibration inputs to negligible levels. However, teetering rotor helicopters have two low-frequency modes, associated with pendulum-like motion of the helicopter body in pitch and roll around rotor main axis. These frequencies for our Xcell 60 with the avionics payload are 2.7 and 3.1 Hz in pitch and roll, respectively, as was clearly seen in power spectral densities of pitch and roll rate signals. Slightly higher roll frequency is due to lower roll inertia. These inputs have amplitudes of up to 6 deg/sec, and are attenuated with digital notch filters. The filters contribute 8 deg phase penalty at the design crossover frequency of 2 rad/sec in pitch and roll axis.

Lastly, high hobby gyro gain leads to increased vibration levels. There are two main reasons for it: airframe flexibility which couples into gyro measurement leading to resonances, and flexible tail rotor servo pushrod, which acts like a second order system, and decreases phase margin in yaw rate control loop. Stiff airframe and pushrod allow use of a much higher yaw gyro gain, which leads to better handling qualities in manual flight.

Future work

Next step on the way to autonomous aggressive maneuvers is to create a wide-envelope helicopter model, adequate for control law design. We will first identify linearized dynamics at hover and forward flight, and then use these results to construct a non-linear helicopter model. The non-linear model will be used in the hardware-in-the-loop simulation to check out control software. As an intermediate step we are planning to implement body axis velocity/heading rate tracking controller, before proceeding to control law design for aggressive maneuvers.

Acknowledgements

David Vos has made numerous contributions to the design of the avionics system. His insight was also essential in elimination of vibration problems.

References

[1] Padfield, G. D., “Helicopter flight dynamics: the theory and application of flying qualities and simulation modeling”, AIAA Education Series, Washington, DC, 1996.

[2] Mettler, B., Tischler, M., Kanade, T., “System identification of small-size unmanned helicopter dynamics”, presented at the AHS 55th forum, Montreal, Quebec, Canada, May, 1999

[3] Bramwell, A.R.S., “Helicopter dynamics”, Wiley & Sons, NY, 1976

[4] Harris, Cyril M., editor, “Shock and vibration handbook”, McGraw-Hill, NY, 1995

Appendix.

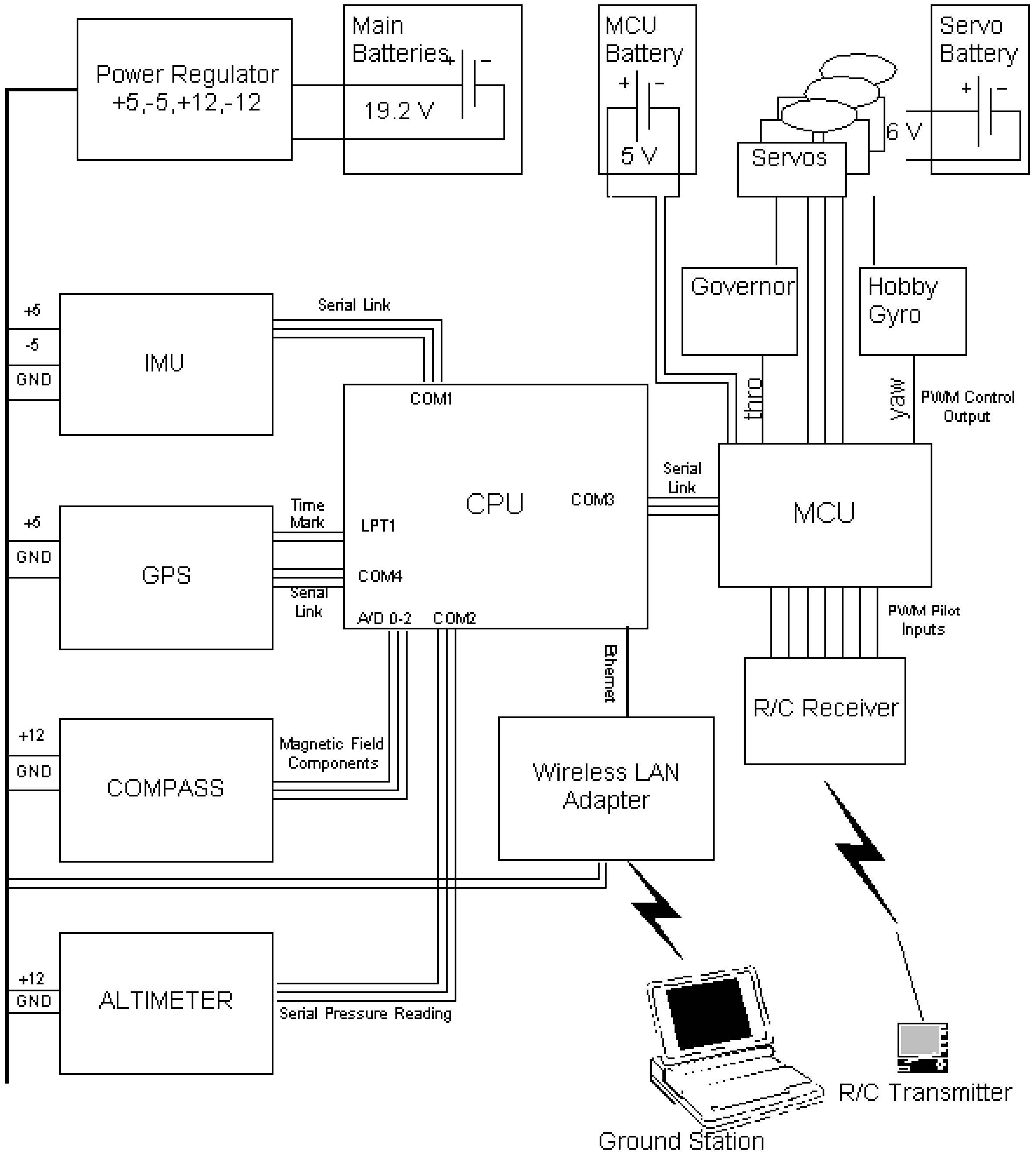

Figure 4. Avionics diagram