Some Key Fundamentals of Classical Control

1. Feedback control is a pervasive, powerful, enabling technology that, at first sight, looks simple and straightforward, but is amazingly subtle and intricate in both theory and practice.
2. In a dynamical system, changes cannot be effected instantaneously, and so an otherwise correct control decision applied at the wrong time could result in catastrophe.
3. An equilibrium point, or operating point, can be unstable, neutrally stable, or stable. Since real systems are nonlinear, a linearized model can be used to approximate a nonlinear system near an operating point. This gives considerable insight into the behavior of the nonlinear system near the operating point.
4. Stability of a dynamic system must be guaranteed, whether the system is uncontrolled or in closed-loop operation. Stability can be determined easily from the linearized mathematical model of the physical model. We call this nominal stability, as it is the model that is determined to be stable, not the actual system.
5. Stable systems have a frequency response. If a stable linear system has a sinusoidal input applied, then the steady-state output will be a sinusoid of the same frequency, however, the amplitude ratio and phase angle of the two sinusoids are frequency dependent. Plots of amplitude ratio vs. frequency and phase angle vs. frequency are called the Bode plots or frequency response plots.
6. The open-loop transfer function, or simply loop transfer function, is the product of all the transfer functions in the loop, i.e., controller, actuator, plant, and sensor. Compared to the closed-loop system transfer function, the open-loop transfer function is much less complex. Therefore, it is much more convenient to use the open-loop transfer function to predict closed-loop system performance, if that is possible. The Nyquist criterion and the Root Locus procedure allow one to do just that.
7. After stability, performance is everything. Command following, disturbance rejection, insensitivity to modeling errors, and insensitivity to unmodeled high-frequency dynamics and high-frequency noise are the main reasons for using feedback control, once a system is guaranteed to be closed-loop stable.
8. Gain margin and phase margin are safety margins for system stability. Stable systems must have adequate stability margins to work once built. Closed-loop systems go unstable because of an imbalance between strength of corrective action and system dynamic lags. The gain margin is the factor by which the gain of a system can be increased, all else remaining the same, before a system goes unstable. The phase margin is the amount of additional phase lag (time delay) a system can have, all else remaining the same, before a system goes unstable.
9. Always conserve phase as time delays can be deadly. Integral control adds 90° of phase lag at every frequency and digital control adds time delay primarily due to D/A conversion. Regarding time delays, imagine trying to make decisions using old information.
10. Beware of lightly-damped poles as arise from compliantly-coupled systems. Every lightly-damped pair of complex-conjugate poles in the plant entails high loop gain near the resonance frequency, as well as 180° of phase shift over a small frequency band.
11. High control gain has lots of benefits, e.g., good command tracking and good disturbance rejection. However, there are three areas of concern: roll-off, saturation, and noise.

12. Practice safe roll-off. If nominal stability holds, one must roll off the loop gain more quickly than plant uncertainty grows. Achieving good roll-off isn't as easy as adding poles to the controller to roll off the loop gain since, as the loop gain rolls off, the loop phase decreases. Hence good roll-off requires that the loop gain decrease adequately without accumulating excessive loop-phase lag. Lead-lag controllers are useful for shaping the loop gain and loop phase to achieve high gain and safe roll-off.
13. Saturation can rob you of both stability and performance. High loop gain is useless if the actuators cannot deliver the specified control signal. Stability margins will be reduced and the closed-loop system may even go unstable. The inability of the actuators to deliver the specified control signal is not just the fault of the controller gain being too high, but rather it is due to both the size of the plant gain and the amplitude of the disturbance signal. If the disturbance signal has a large amplitude, then the actuator may saturate and you will have no choice but to reduce the gain of the controller and thus sacrifice performance.
14. High gain amplifies noise. An integrator tends to smooth and attenuate noise, while a differentiator tends to amplify noise. Every pole in a transfer function is like an integrator, while every zero is like a differentiator. As the plant gain rolls off, you may wish to include zeros in your controller in order to increase the loop gain for better performance while adding phase lead to the loop transfer function in order to increase the phase margin for robust stability. Zeros will do both of these quite nicely. However, the resulting high controller gain will now amplify noise in the measurements, and this amplification may outweigh the performance and stability benefits of the high loop gain and loop-phase lead.
15. Multi-loop control is nontrivial. Multiple control loops are needed whenever a plant has multiple sensors or actuators. In this case the interaction of every feedback loop with every other feedback loop must be accounted for. The performance benefits of multi-loop control, however, are often far more than one would expect from a collection of single-loop controllers.
16. Nonlinearities are always present. Real systems have all kinds of nonlinearities, e.g., backlash, Coulomb friction, saturation, hysteresis, quantization, dead band, and kinematic nonlinearities. Thus a controller designed for a linear plant model to satisfy performance specifications may perform poorly when applied to the actual plant.
17. People's lives may be at stake. Real control systems must be extremely reliable, especially if people's lives depend on them.