Dynamic Control of Optical Systems

Keith Powell
Steward Observatory
(520) 626-4323
kpowell@as.arizona.edu

Topics

- Why controls for optics?
- Basic concepts of control systems
- Example 1: Camera image stabilization
- Example 2: MMT Optical Line of Sight control
- Summary

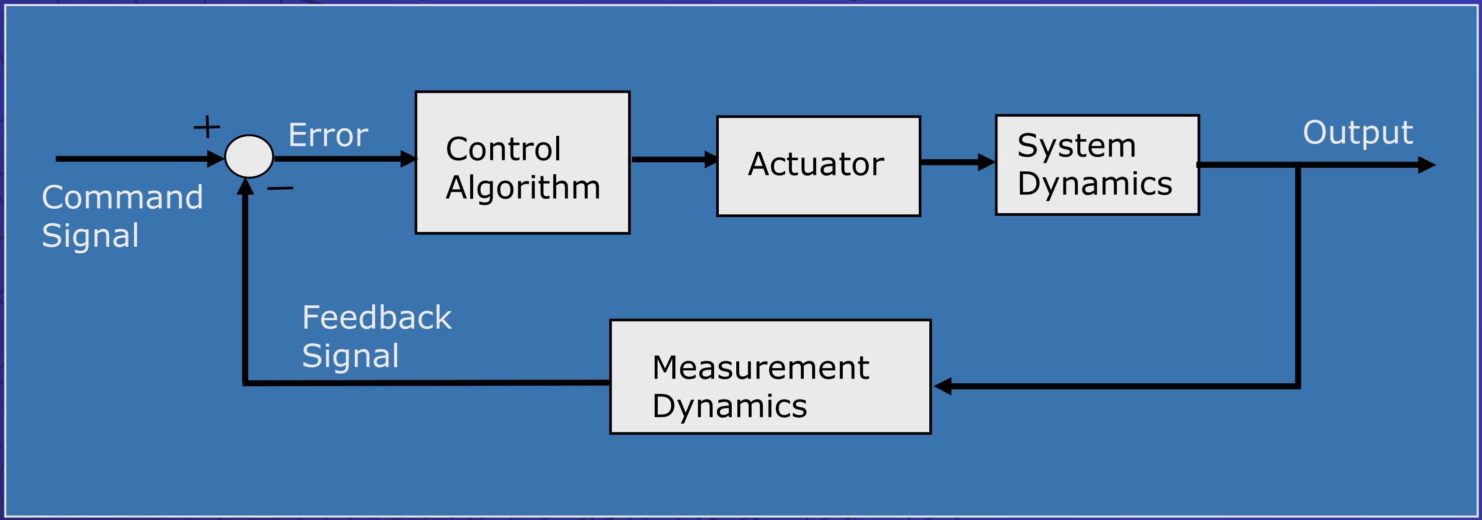
Why Controls For A Course in Practical Optics?

- Dynamic control is ubiquitous in optical systems – It's practical!
  - Pointing control for telescopes (wind buffeting)
  - Active aberration correction in lithographic lenses
  - Control of quantum systems using Lasers
  - Active controls for testing and polishing mirrors
  - Adaptive optics
  - Laser Guide Star stabilization
  - Camera image stabilization
  - MMT Optical Line of Sight control (Jitter control)
  - Many more…

Two Types of Control Systems

- Open loop control
  - Applies correction based on precalibrated algorithm
    - Telescope examples
      - Compensation for atmospheric refraction
      - Gravitational sag in telescope structure
- Closed loop control (Feedback)
  - Utilizes measured parameter to form an error signal. The error signal is then used to alter the system dynamics in real time
    - Aircraft guidance or autopilot
    - Thermal control of optical elements
    - You driving your car (unless you're talking on your cell phone)

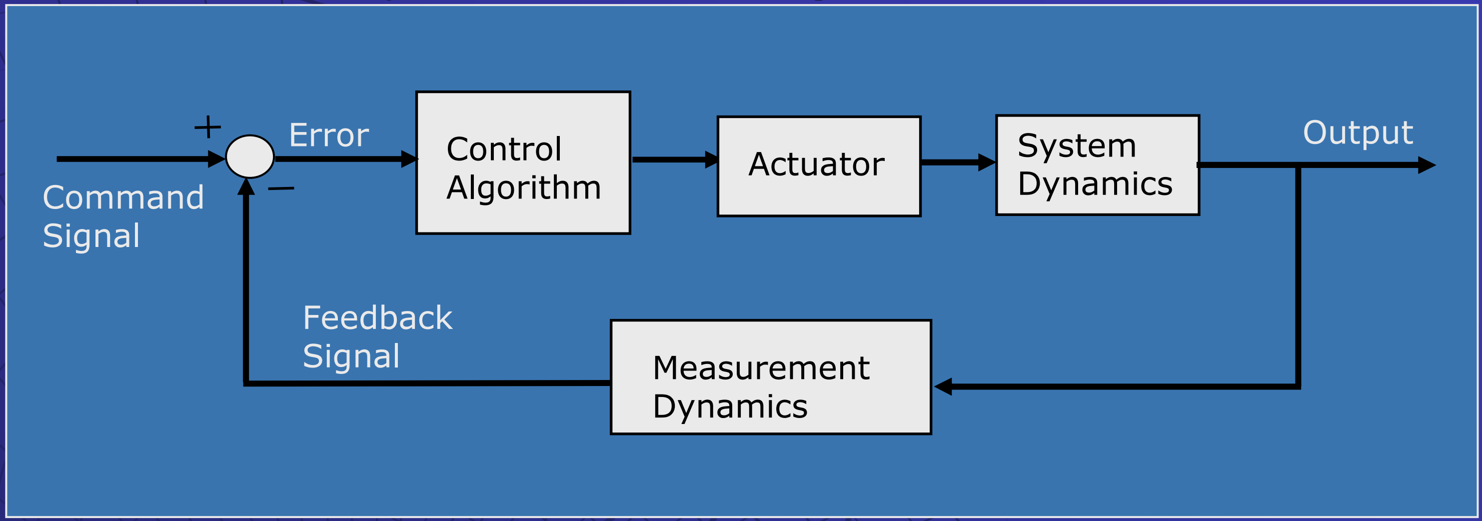
Basic Closed Loop Control System Components



- Control algorithm – Usually software on computer. Many different controller topologies. PID control is by far the most common

- System dynamics – Mathematical model of components being controlled (e.g. motion of lens elements, deformable mirror, telescope, etc.)

Basic Closed Loop Control System Components II

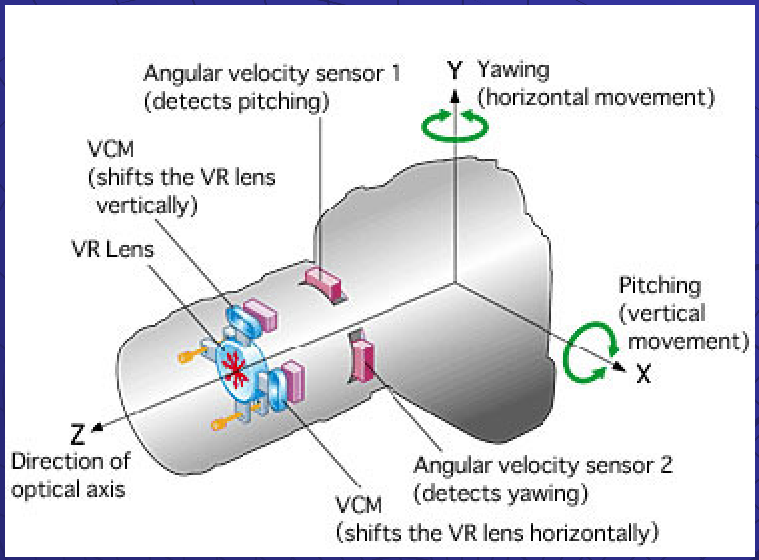


- Measurement device – Provides an estimate of the physical parameters being controlled (rate gyros, accelerometers, position sensors)
  - Can introduce scaling errors, biases, and noise
- Actuation device – The device which provides the corrective motion to the system (piezoelectric actuator, voice coil motors, etc.)
  - Has limited bandwidth (finite response time)

Advantages and Disadvantages of Closed Loop Control Systems

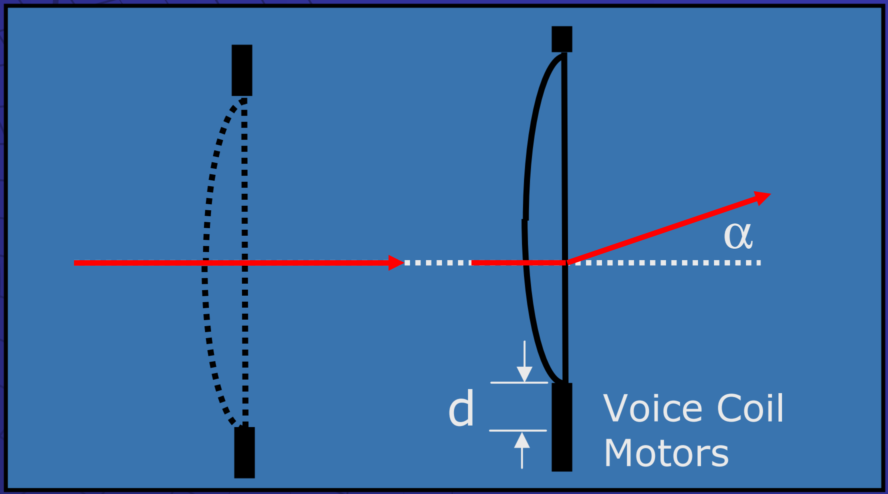
- Advantages
  - Significantly increased accuracy
  - Reduced sensitivity to external perturbations
  - Reduction of nonlinear effects such as friction in telescope drives
  - Increased response bandwidth
- Disadvantages
  - Requires sensing and control devices which can be expensive
  - Software development and implementation
  - Can become unstable if not properly designed – MMT pointing controller has significant issues

Example 1: Camera Image Stabilization



- Control algorithm - Built in microprocessor
- Measurement device – Two orthogonal rate gyros
- Actuation device – Two orthogonal voice coil motors

- Voice coil motors used to decenter lens by distance=d and cause ray deviation at angle α



Stabilization System Reduces Image Blur

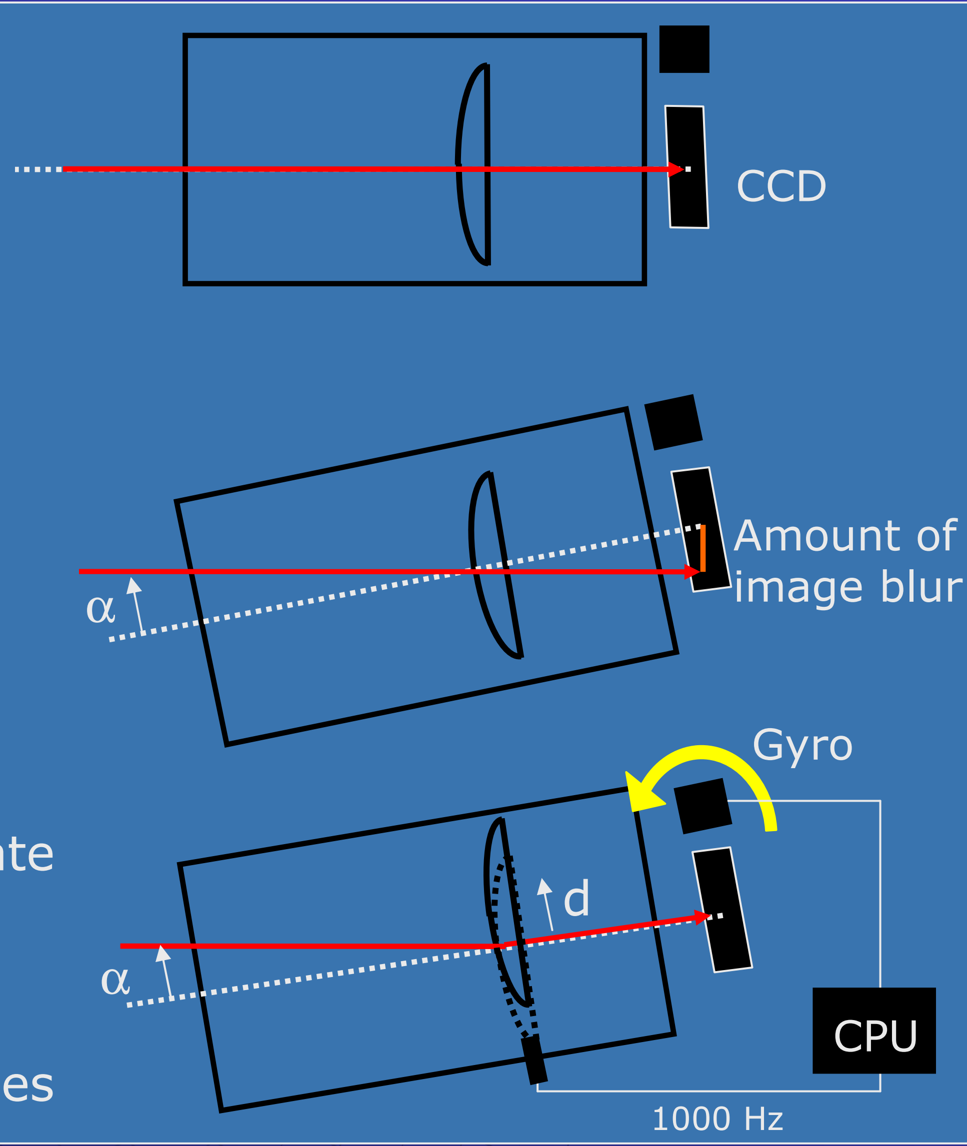
t=0 Shutter opens

Rate gyros measure zero angle

t=t1 Shutter closes

Image stabilization OFF – no compensation for angular deviation

Image stabilization ON – Rate gyros measure angle of rotation α and displace lens upward to continuously compensate as angle changes



Camera Image Stabilization Issues

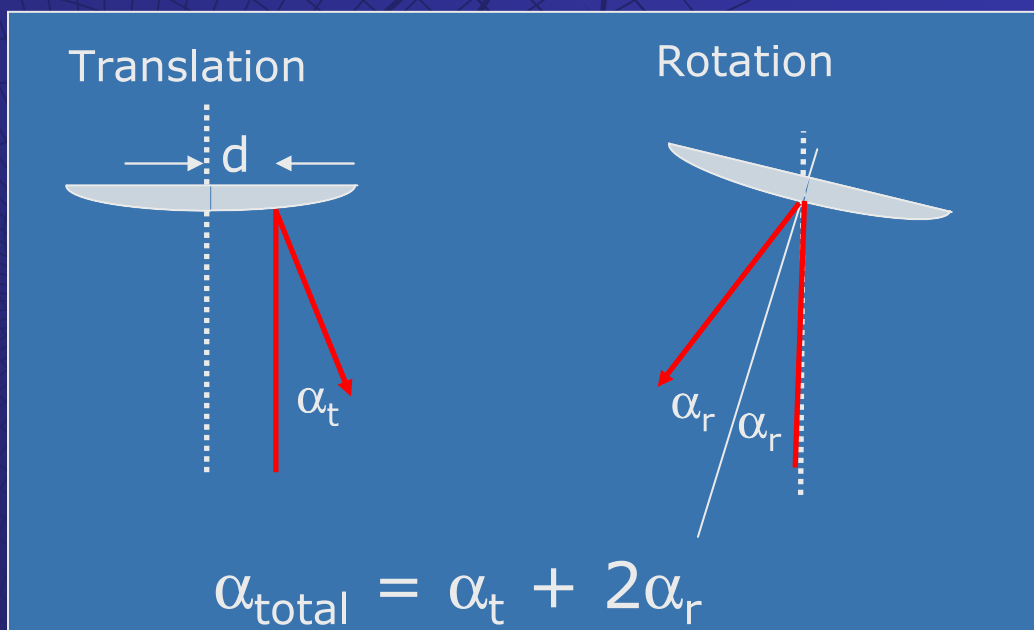
- The angular velocity sensors have biases which cause lens drift over time. The Nikon VR II system recenters the lens just prior to shutter release to maximize optical quality
- Older control algorithms have problems when mounted on tripods due to high frequency vibrations outside the bandwidth of the controller. Software and sensor upgrades have greatly mitigated this effect in current systems
- The angular velocity sensors are also being upgraded to have better low frequency response characteristics to allow greater attenuation of image motion

Example 2: MMT Optical Line of Sight Control

- The MMT has a structural vibration at ~19 Hz which severely degrades the image quality during adaptive optics runs
- The vibrational mode causes translation and rotation of the AO secondary with respect to the primary mirror
- Movement of the secondary mirror is manifested as image motion (or jitter) of ~40 milli-arcseconds peak at the sensor. This is currently the dominant error source for AO

MMT Secondary Motion Translation and Rotation

- Translation and rotation each contribute to the overall image motion seen at the sensor.
- The calibration factors due to translation and rotation of the secondary are computed in Zemax independently then added together to form the total required correction to the control device, in this case, a deformable mirror

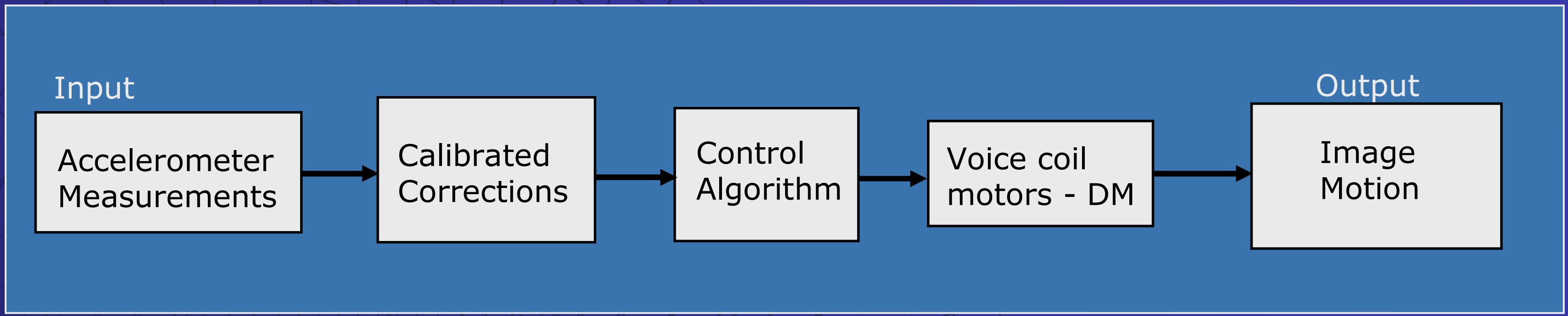


Optical Line of Sight Control Approach on the MMT

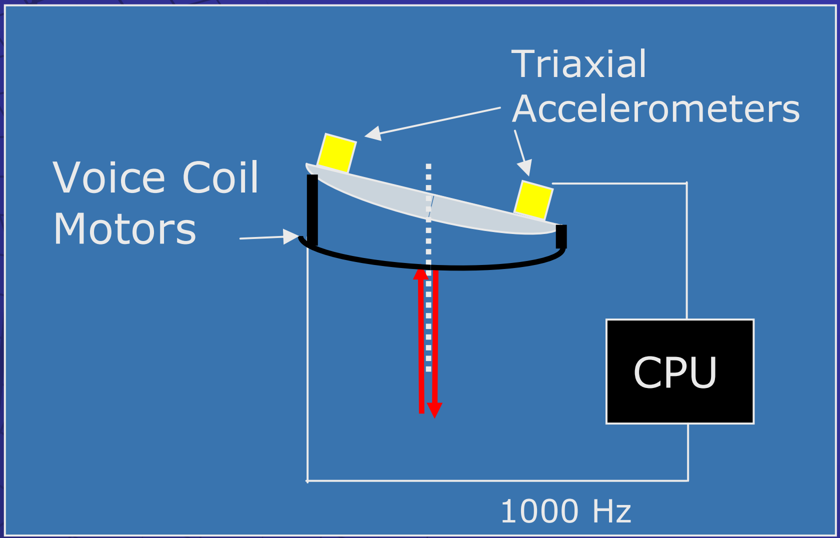
- MMT optical LOS control is very similar in its approach to the camera image stabilization problem
- Accelerometers are placed on the back of the AO secondary which measure its displacement with respect to the primary mirror
- We can calibrate the amount of translation and rotation of the secondary to the image motion seen at the sensor.
- Use relations between secondary translation and rotation to compute a correction command to the DM which cancels out the image motion

MMT Optical LOS Control

Accelerations from the sensors are integrated to form position and velocity estimates. These parameters are then used in the controller to tell the deformable mirror what motion is required



- This is an OPEN LOOP process!
- The controller relies on the calibration factors to convert the measured accelerations into image motion via the DM



Simulated Image Motion with Optical LOS Control Off/On

- MATLAB simulation created to evaluate various controller algorithms
- Initial controller reduced the closed loop image motion by approximately a factor of four
- Current algorithm will attenuate image motion by a factor of twenty

MMT Optical LOS Issues

- Accelerometers typically have low frequency biases which results in drift over time. This can be bad in an open loop controller
  - Can compensate by filtering low frequency data to remove drift
  - Can use centroid data from image to recenter the controller command
- Finite actuator response time limits the amount of achievable attenuation
- WFS noise limits the update rate and amount of gain (or correction) one can put into the system

Summary

- Future Telescope Applications
  - Active and adaptive optics systems will be on all new major optical telescopes (MMT,LBT, GMT, etc.)
  - Large Telescopes will REQUIRE active control of the optical line of sight due to structural vibrations
  - More sophisticated control algorithms required to integrate individual components (active, adaptive, LOS control, etc.) and improve system performance
- Dynamic control of optical systems will become more prevalent in the future
  - Sensor/actuator cost and size decreasing
  - Computing power increasing
  - Maximize the performance of optical systems

Questions?

Backyard 9 inch reflector with Stellar Visions Adaptive Optics system