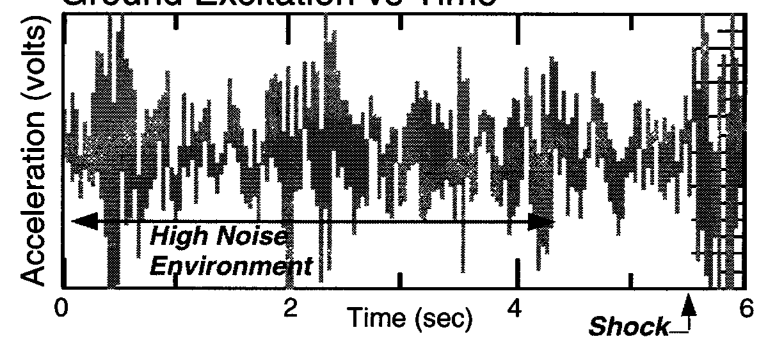
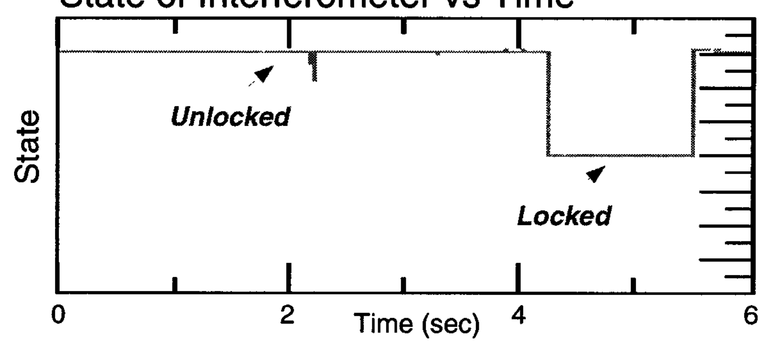
ADVANCED CONTROL TECHNIQUES: MOTIVATION

- Challenging detector availability goals have been established for the LIGO observatories:
  - ›› Single interferometer operations > 90% of the time with minimum of 40 hr. continuous lock periods
  - ››Double coincidences > 85% time and triple coincidences > 75% time with 100 hr. minimum continuous lock periods
- 40 m prototype experience:
  - ››Limited periods of continuous interferometer lock will be the main contributor to detector down-time (40m prototype lock durations vary from seconds to a few hours)
    - —Control system instabilities caused by drifts in the interferometer system parameters
    - —Displacement noise events which kick the interferometer out of lock

Ground Excitation vs Time



State of Interferometer vs Time



ADVANCED CONTROL TECHNIQUES: BACKGROUND

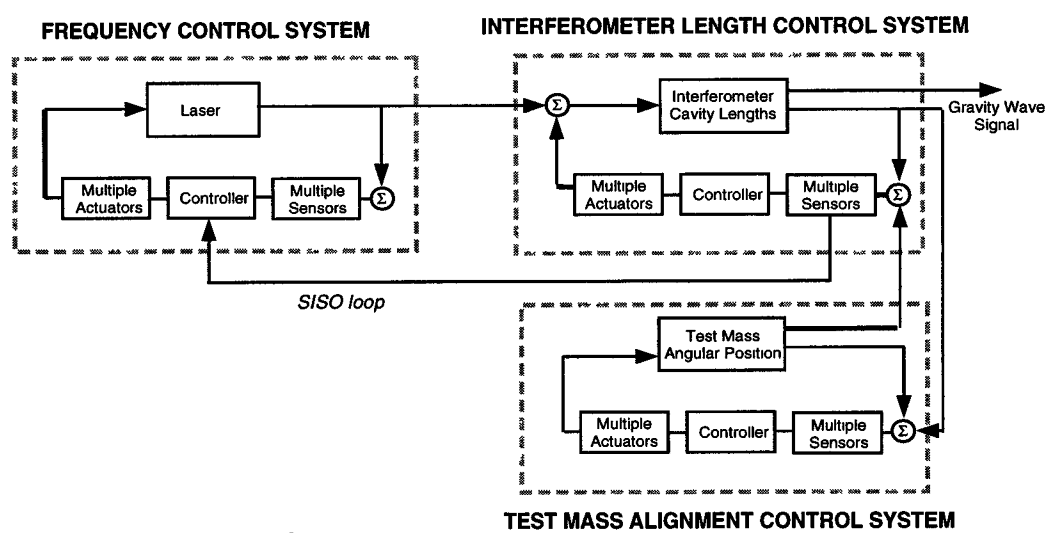
- LIGO has frequency, length and alignment servo-control loops

  ›› The optical model for the length control system is a 4x4 matrix of transfer functions:

$$H_{ij}(s) = G_{ij} \cdot \frac{\left(1 + \frac{s}{z_{ij}}\right)}{\left(1 + \frac{s}{p_{ij}}\right)}$$

The 4 degrees of freedom are the common mode arm cavity length *L+,* the differential arm cavity length *L-,* the Michelson difference *l-,* and the Michelson common mode length *l+*

›› The interferometer optical alignment model is a 10x10 matrix of transfer functions whose elements have a similar form

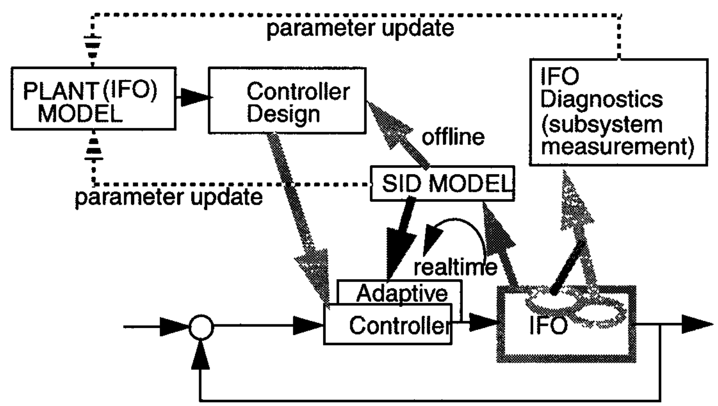


ADVANCED CONTROL TECHNIQUES: BACKGROUND (continued)

- Potential hardware imperfections, model errors, unknowns or parameters subject to drift which could effect control system robustness include:
  - Beamsplitter reflectivity ≠ 50%
  - Mixer phase error
  - Deviations from resonance
  - Visibility variation
  - Fabry-Perot cavity input and end test mass absorption (resulting in radius of curvature changes)
  - Sensor & actuator cross-talk (optical, mechanical & electrical)
  - Alignment/length Coupling
  - Modulation depth & phase variation

ADVANCED CONTROL TECHNIQUES: STRATEGY

- System identification will be used in conjunction with subsystem diagnostic and measurement techniques to update our understanding of the system and its control
- Once the system susceptibilities are understood, an adaptive controller can be formulated to compensate
- SID and Adaptive Control are mature technologies;
  The application to Interferometry is unique

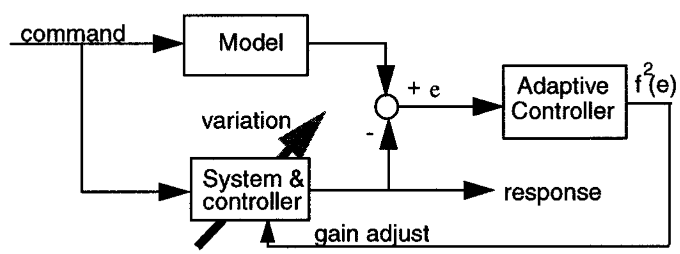


ADVANCED CONTROL TECHNIQUES: SYSTEM IDENTIFICATION

- System identification (SID) is an empirical approach to modeling interferometer system dynamics
  - Non-parametric identification (i.e. frequency response estimation)
  - Parametric system models (e.g. state space representation)
- For LIGO we seek a recursive, real-time parameter identification of the multi-input/multi-output optical response of the interferometer in Detection Mode:
- Many techniques are available and will be explored; Potential candidates include:
  - Generalized Least Squares and Maximum Likelihood Estimators (e.g. the Prediction Error Method) are computationally simple
  - Observer/Kalman Filter Identification (OKID) -- time domain based, can be extended to identification of closed loop effective controller/observer combination (Observer Controller Identification, OCID)
  - State-Space Frequency Domain (SSFD) identification -- frequency domain based (can use spectrum analyzers)

ADVANCED CONTROL TECHNIQUES: ADAPTIVE CONTROL

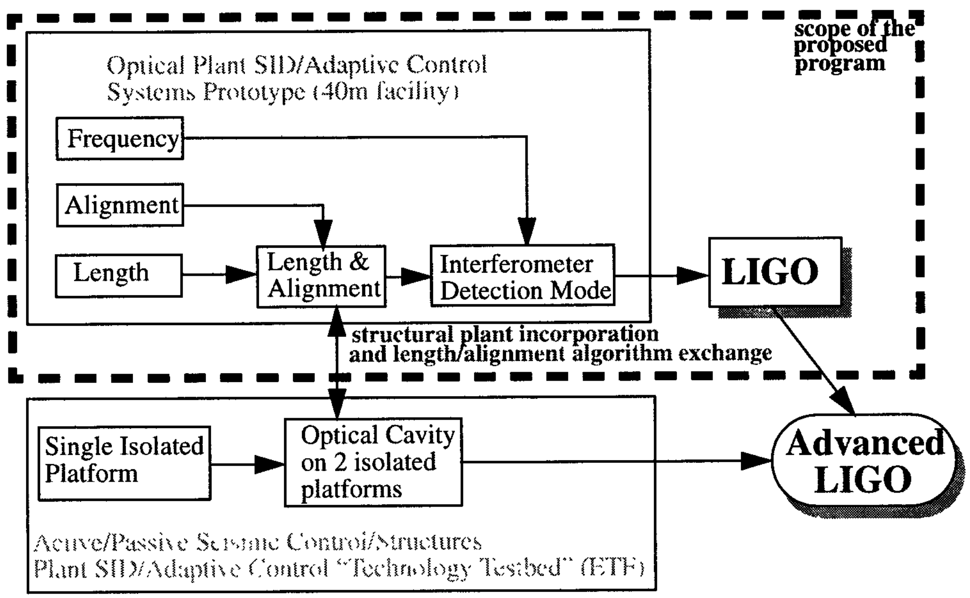
- Adaptive Control can improve sensitivity while maintaining robustness to disturbances and plant variations
- Adaptive control time scales:
  - »milliseconds for the ordinary feedback
  - »many minutes for updating the control parameters and performing SID
- Possible adaptive control algorithm: Model Reference Adaptive Control



ADVANCED CONTROL TECHNIQUES:

COLLABORATORS & RESPONSIBILITIES

- Stanford Univ. plans to explore system identification and adaptive control on advanced seismic isolation and suspension subsystems
- LIGO will concentrate on identification and control (length, alignment and frequency) of the optical plant for a power recycled configuration



- GEO plans to explore adaptive control for autonomous and tele-remote operation

ADVANCED CONTROL TECHNIQUES: WORK PLAN

- System Identification:

  ››The 40 m prototype will be used as the principal testbed for different SID schemes (ETF as secondary testbed for single cavity length/alignment control)

  ››Sequence:

  1. Investigate and categorize events/sources that unlock the interferometer
  2. SID for four length loops separately to identify model parameters (poles, zeros and gains)
  3. Length system as a Multi-Input Multi-Output (MIMO) system, including cross-couplings between the loops
  4. Establish whether ambient, in-situ, stochastic excitation is sufficient for determining the model parameters with required accuracy -- or establish calibrated external stimulus requirements/design
  5. SID for wavefront sensor based alignment system (MIMO system)
  6. SID for combined length and alignment system
  7. SID for frequency control system
  8. SID for entire system

  ››Off-line SID can be accommodated with the current 40 m data acquisition (DAQS) system

  ››The 40 m DAQS can also be used, with additional real-time software & hardware (VME processor and DSP), to perform recursive SID

  ››Once an on-line method has been tested and verified on the 40 m prototype it will then be adapted to LIGO (add IO length and alignment control)

ADVANCED CONTROL TECHNIQUES: WORK PLAN (continued)

- Adaptive Control:
  - The 40 m prototype will serve as a testbed
  - Control will be made adaptive, where beneficial, based upon analysis of SID results
  - Requires the planned 40 m electronics retrofit with “LIGO-like”, VME-based, digital controls
  - Computation will be implemented on another dedicated VME processor with an associated Digital Signal Processor (DSP), networking board and reflective memory
  - Once the adaptive control is demonstrated to improve 40m prototype performance, it will be ported, with necessary changes, to the initial LIGO interferometer system
- The performance of the system in terms of availability (increased lock acquisition time) and decreased noise level will be compared in a series of long duration (order of a week) data runs

Advanced control plan milestones and dates

Milestone	*Target*
SID application to 40m	6/99
Adaptive Control application to 40m	6/00
SID application to LIGO	12/99
Adaptive Control application to LIGO	6/01