SOME THOUGHTS ON MACHINE LEARNING FOR GW DETECTOR CONTROL SYSTEMS

CONTROLS WORKSHOP

GWADW

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PLAN OF ATTACK … perhaps obvious

• Formulate suitable target problems including metrics or requirements
  • Rana et. al. have identified some suitable problems
  • Hope to discuss & expand target problem list in this workshop

• Create or identify a ‘test bed’
  • A model or simulation that represents the plant and its disturbances, including the variations which warrant adaptation, and/or
  • A physical emulator (e.g. LASTI or 40m Lab systems)

• Identify a suitable ML technique(s)
  • Discuss experience from the GW community in application of ML techniques in this workshop, e.g. DetChar has applied ML techniques – are they applicable to our control problems?

• Pair up problems & ML techniques with volunteers

• Continue pursuit through the Control Systems Working Group (CSWG) monthly meetings
  • All GW community members are encouraged to participate
SOME THOUGHTS REGARDING MACHINE LEARNING (ML)

- ML is most often not applied to control problems
  - Classification / Clustering
  - Image recognition / Pattern recognition
  - Data mining / Deep Learning
  - Optimization / Minimization

- When applied to control, it is generally for the purpose of
  - Adaptation of control parameters
  - System Identification
  - Few examples of application to complex MIMO systems

Towards Automated Control

INTRODUCTION:
The manual tuning of hundreds of control loops can become a delay in interferometer commissioning. We present here an effort towards a technique to address this delay.

Ultimately, we would like to formulate an optimal control problem that allows us to incorporate arbitrary information about the controller requirements and constraints (inspired by [1]). Our current approach can be divided into three steps:

- Write a cost function that incorporates the goals and requirements for the particular control task.
EXAMPLE: BOSE-EINSTEIN CONDENSATE (BEC) MACHINE


- Machine-learning online optimization (MLOO)
  - Real time optimization
  - Creates an internal statistical model (fits to previous observations)
  - Models the experiment using a Gaussian process (GP)
  - Chooses to do future experiments that will best refine its model, making it an automation of scientific method (Oh No! We’ll all be out of jobs!)
ADAPTIVE INVERSE CONTROL CONCEPT

- Concept developed by Widrow & Walach (~1971 - 1986) and then married to neural networks (late 80s, early 90s)
- Adapt the controller (adjust its parameters) until the error is small, i.e. until the controller is the inverse of the plant
- The adaptation algorithm uses an objective such as minimizing the mean square error
- The adaptation is a form of feedforward control
- If the plant has delays, then the controller must be a predictor
- If the plant is non-minimum phase, then the inverse controller would be unstable. However one can introduce a suitable delay and realize a delayed plant inverse

**Diagram:**
- Command input → CONTROLLER → Plant input → PLANT → Plant output
- ADAPTIVE ALGORITHM
- Error (sum of plant disturbances and sensor noise) is not suppressed

N.B.: as shown plant disturbances and sensor noise are not suppressed
MODEL-REFERENCE ADAPTIVE INVERSE CONTROL WITH PLANT NOISE AND DISTURBANCE CANCELING

• A reference model is chosen to have the desired system response

• Plant noise and disturbances are cancelled by feedback through an inverse plant model

• Requires 3 adaptation processes

• Objective function must be chosen carefully to whiten and/or filter the error

• Inverted plants are notoriously non-robust due to plant variation → the adaptation rate must be fast
EXAMPLE: MIMO APPLICATION OF ADAPTIVE-NOISE CANCELATION

• Beam Trajectory control for the SLC (SLAC Linear Collider)
  Ref: B. Widrow, E. Walach, Adaptive Inverse Control, 1996.

• Beam centering
  • Passive: set of 300 Quadrupole electromagnets focus the beam
  • Quasi-DC dipole electromagnets (V & H sets near each quadrupole) steer the beam
  • Capacitive Beam Position Monitors (set of 300) used to calculate drive amplitudes for the quasi-DC dipole magnets
  • 20 Steering feedback loops, in sequence
    • Each controls measures & controls 8 states: position & angle, in V & H, for e⁻ and e⁺
    • 20 Hz sample & update rate (120 Hz beam pulse rate)
EXAMPLE: MIMO APPLICATION OF ADAPTIVE-NOISE CANCELATION

- LQG optimal filters to minimize beam position RMS
- 7 sequential loops
- Consider “upstream” \{positions, angles\} as noise — Loop \( n \) corrects for these errors, Loop \( n+1 \) corrects for errors due to transport (or residuals after Loop \( n \))
EXAMPLE: MIMO APPLICATION OF ADAPTIVE-NOISE CANCELATION

• Least Mean Square (LMS) Algorithm for updating the weights (matrix elements)
  • Only stable if the learning rate is less than the inverse of the largest eigenvalue on the input correlation matrix
  • Magnet supply & klystron fluctuations can cause jitter amplitude to increase 10x in short time, hence eigenvalues change proportionally → leads to a low learning rate and slow convergence
  • LMS has different convergence rates for each eigenmode

• Sequential Regression Algorithm (SER)
  • Adaptively estimates the inverse of the correlation matrix
  • Scales the inputs so that all the eigenvalues of the correlation matrix of the scaled inputs are unity (solves both problems of the LMS algorithm)
  • However calculated weights are unstable initially when large updates occur; Delay updating weights until converged
GW DETECTOR PROBLEMS ‘RIPE’ FOR ML?

• Angular controls
  • Angular loops introduce noise to DARM by the beam off-centering
  • DC coupling is removed by the coil balancing (angle to length feedforward)
  • AC coupling due to unsuppressed angular motion, and imperfect balancing
  • Bandwidth limited to keep angular control noise injection low
  • Let ML adaptively adjust feedforward gains for the unsuppressed angular motion (ASC error point)? (Essentially a time-varying coil balancing)

• Interferometer Global control parameters
  • Let ML tune up the global controls, just as an operator does …
  • Blends, Michelson feedforward, ASC bandwidth, bounce/roll servos, …
  • Based on the seismic noise in a particular band, wind speed, …

• TCS control
  • Compensate for TM radius of curvature when IFO is locked or transitioning in and out of lock
  • Let ML discover the model, or predictor, for TM thermal lens

• Others?