Plasma Control on Existing Devices
Experience Gained

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- Useful definition of control
- Early control
- Evolution of equilibrium control through to today - experiments
- Evolution of equilibrium control through to today - modelling
- Emerging pattern
- Outstanding issues

- Sorry, no citations, this is not a review, not even *** is mentioned !

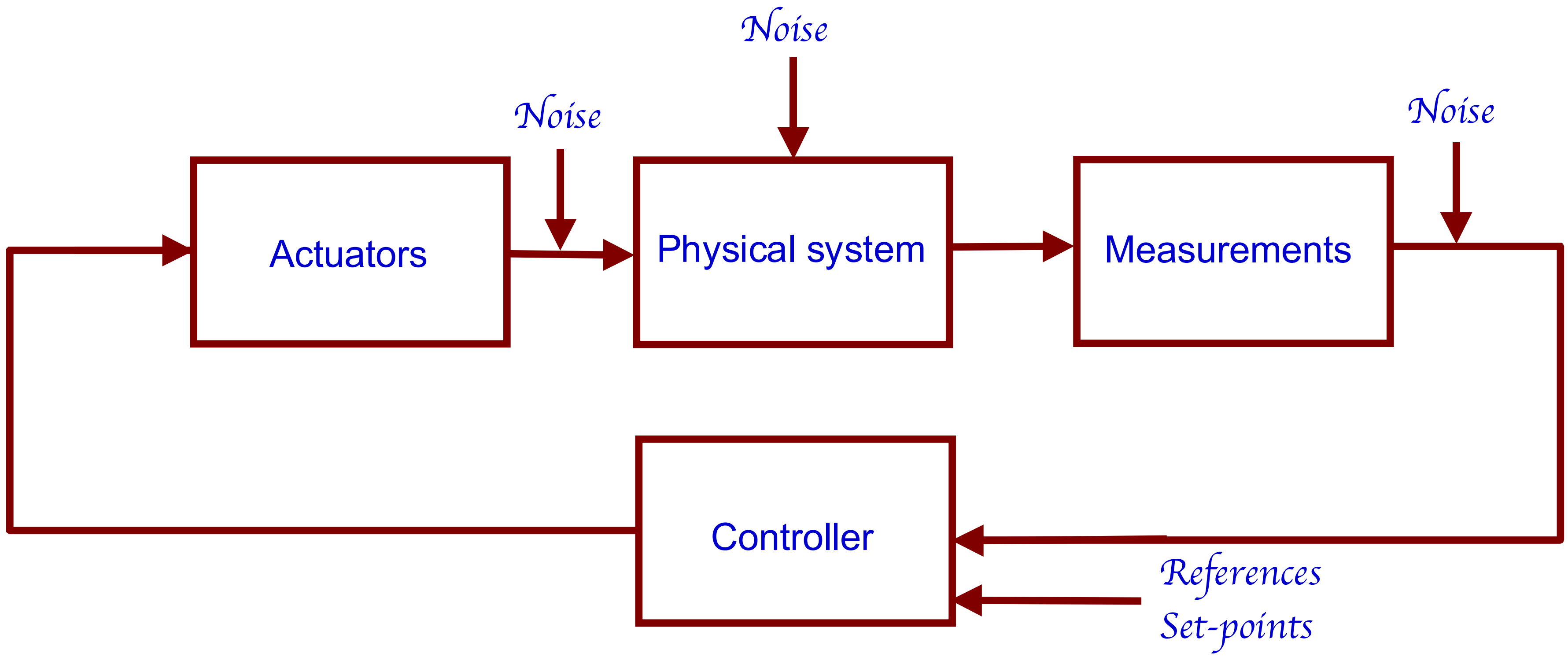
Useful definition of feedback control for our purposes

- "Moving the state of a system from a given state to another state in a finite time"....and less formally.....

- "Changing the parameters from their natural values to desired values, within a useful time delay and within the limits of the actuators"

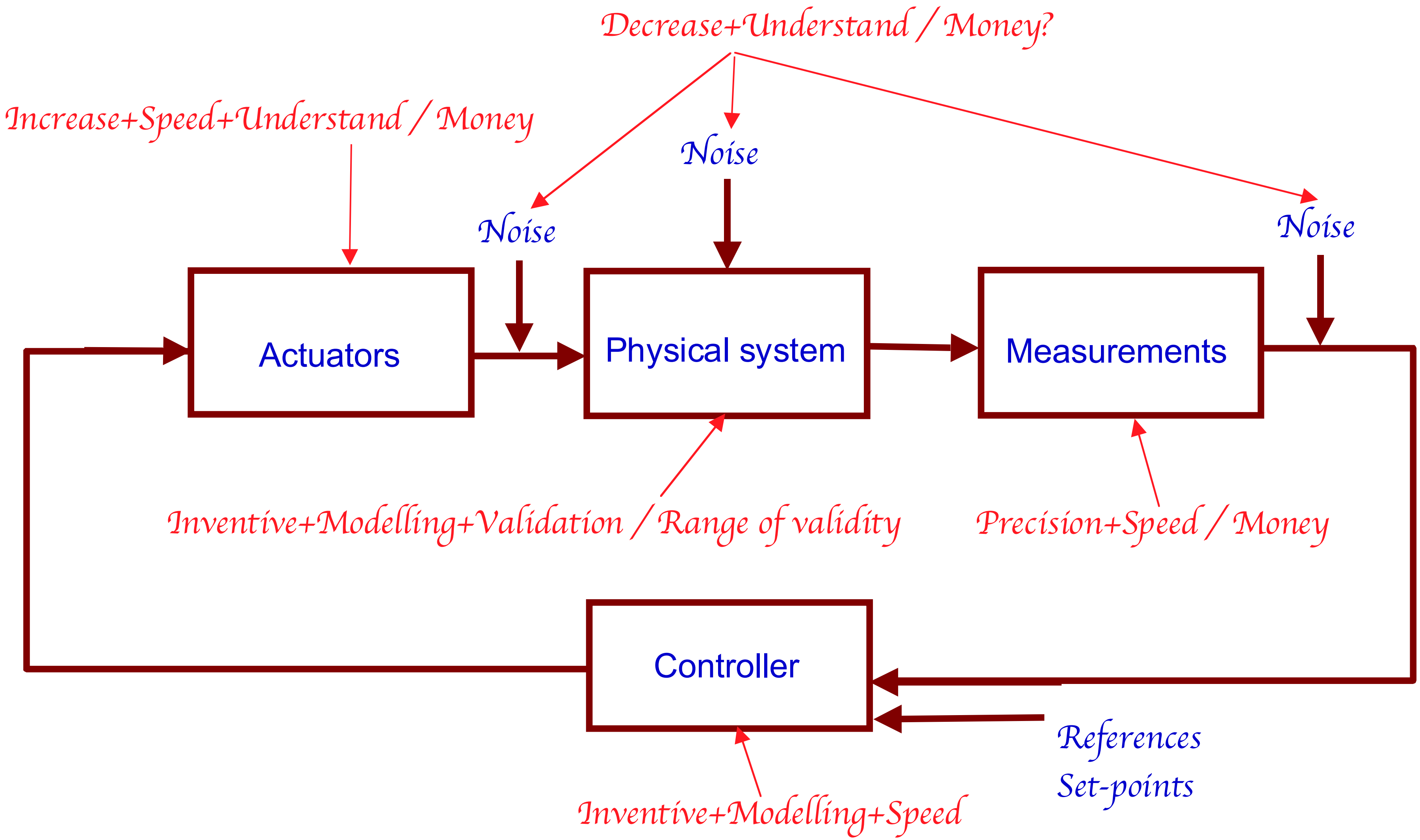
- We therefore exclude trivial cases such as:
  - Control of the ohmic current profile in steady state by an electric field
  - Control of the steady state plasma density profile using a gas valve

Schematic of feedback control for our purposes



- This picture can be the real thing to control
- It can be the full model of the thing to control
- It can be a linearised model of the thing to control
- It can be a simplistic model of the thing to control

What have we learned ?



Evolution of equilibrium control - 1

- First came circular plasmas
  - Preprogrammed vertical field and transformer current, gas pre-fill
    - Problem, hitting the wall when parameters change
- Feedback control of radial position
  - Feedback on the radial position, using the Shafranov equation for the vertical field model, assuming time-varying β and l_i
    - Problem, sensitivity of operation to q, lack of current control
- Feedback control of plasma current
  - Feedback on Ip, via the transformer primary
- Most of the problems were electrotechnical, to have the controllable actuators, moving from capacitor banks to thyristor supplies
- No real difficulties, measurements OK, system stable - errors were only drifts and offsets, easily recovered “à la Russe”

Evolution of equilibrium control - 2

- Then came non-circular plasmas and partial redundancy of coil currents
  - Problem 1 - need to diagnose the shape or other equilibrium parameters
  - Problem 2 - systems are no longer orthogonal like B_v, I_{oh}, B_r, B_t
- Problem 1 was solved by
  - Estimating the gap between separatrix and wall, using Bpol flux extrapolation
- Problem 2 was solved by
  - Either using the nearest coil and hoping the system was roughly diagonal
  - Or setting up a "decoupling matrix" to feed the error to several supplies
  - Or controlling the vacuum field and plasma position separately

Evolution of equilibrium control - 3

- Difficulties
  - Precision of the gap estimators
    - Development of neural networks, function parameterisation, ad hoc fitting, real time reconstruction
  - Precision of the decoupling
    - Development of better models - validation of models (rather robust = tolerant to differences between model and reality)

- The integrating nature of the system, V » I, means that the feedback recovers from the general imprecision of the models used for decoupling
- In fact, even the vacuum response works really quite well on several tokamaks - the ultimately simple response model
- Therefore we could be rather heavy-handed

Evolution of equilibrium control - 4

- Systems were pretty stable (exception of the iron core attraction)

- Increasing the elongation brought the new challenge of instability
  - Shaping tended to go hand in hand with elongation, which leads to the vertical positional instability
  - In the beginning, modelling was extremely simple (3-equation rigid current model), but was close enough to the reality to generate the required estimates for the elongated tokamak designers and intuition for the tokamak operators
  - Elongation was increased experimentally with “little difficulty” on the basis of this simple modelling

Evolution of equilibrium control - 5

- Dynamics of the shape controller
  - Ip, shape and radial position control are reasonable with feedforward programming plus proportional control - the system is stable
  - Adding low frequency gain allows the feedforward programming to be less precise and reduces drift and offset
  - Adding derivative gain speeds up the response - just a few “knobs”
- Dynamics of the vertical position controller
  - Proportional gain is inadequate above a certain critical elongation and derivative control is essential
  - The bandwidth of the diagnostics now becomes important, since we can no longer filter to “clean up” the power supply demand signals
  - Delay in the loop kills - design criterion on diagnostics/actuators/controller

Evolution of equilibrium control - Balance sheet

- Credit - satisfaction
  - The methodology described up to now, corresponding to mid-1990's, allows fairly highly shaped plasmas, fairly highly elongated plasmas, fairly accurate current control and "some" operational flexibility
- Debit - more work to be done
  - Power levels were increasing and the precision required by the experimental programme was increasing
  - The effect of large disturbances on large tokamaks too frequently led to loss of control and VDE's
  - ITER was on the horizon

Advanced equilibrium control - 1

- Diagnostics
  - It was realised that diagnostic precision was not always adequate
    - Real-time reconstruction has been implemented on several devices
    - Work was done on improving the magnetics
- Controller dynamics
  - Control theory predicts that higher performance can be obtained given a higher order controller and a "sufficiently" accurate model
    - Model validation was undertaken - different models, different tokamaks
    - High order controllers were demonstrated, but no free lunch
    - Work often concentrated on optimising closed loop performance at a fixed operating point

Advanced equilibrium control - 2

- Coil current problems
  - More extreme shapes could be theoretically obtained in existing tokamaks, but they required exploring coil-current space where the relationship between shape and currents is less linearisable
    - Approach was rather seat of the pants
    - Some difficulties were experienced
    - Currents could be close to the limits
    - Mix between controller design and pragmatism is universal

- Coil voltage problems
  - As the performance requirements increased, the coil voltages were saturating with disturbances and the total power demand was increasing
    - Work is being done on voltage saturation control - pipeline
    - Work is being done on "power management" to limit the total reactive power - pipeline

Towards ITER - what is the status ?

- Long pulses
  - Ironically, early tokamaks had integrator drift problems, solved by integrating other drift-free diagnostics
  - We are more or less long pulse in terms of L/R
  - The same approaches to diagnostics will be necessary for ITER, combining drift-free low frequency responses with the magnetics
- Precision
  - The scaled precision of the long-pulse control appears reasonable, but we do not have a totally convincing integrated demonstration yet (?)
- Modelling
  - Some of the models in use today would appear to be adequate to describe present experiments and be confident about predicting ITER
- Controller design
  - Many methods exist and seem to work adequately
  - Problems will be delay, saturation, disturbance recovery and precision

Method of progressing in the past

- Shape and current control presents few serious technical difficulties, given adequate care and attention

- Progress has been made on shape and current control by
  - Trial and error
  - Simple modelling
  - More trials, fewer errors
  - More accurate, higher bandwidth measurements
  - More accurate dynamical modelling
  - More attention to the dynamics of controller design

Towards ITER - equilibrium integrated control

- Particularities of equilibrium control
  - Equilibrium response models are well linearised, well understood
  - Lumped (non-diffusive) models are accurate
  - High quality, low delay, linear (+-) actuators
  - Knowledge of the impact of controller design on system power requirements
- Particularities of profile control
  - Naturally diffusive
  - Very coupled action of the actuators
  - Highly non-linear (0+) and saturated actuators
  - Weak diagnostic information and precision

Towards ITER - What haven't we done yet ?

- Pending items
  - AC losses optimisation only modelled - new devices pre-ITER ??
  - Power management only modelled - all devices ??
  - Saturation only modelled - all devices ??
  - Breakdown phase only weakly modelled - ??
- Nuclear systems
  - We have not yet demonstrated a nuclear environment approach to plasma control
    - Preparation
    - Validation
    - "guarantee"
    - Autopsy
  - Even the largest devices accept an unacceptable failure rate
- ITER will need to integrate plasma control into a "shuttle" mentality