# Reasons to integrate controls with system design

## I. Guiding principals
1. The control is part of the system. For good system performance, you must design the system to be controlled.
    a. X to RY mechanical coupling has been minimized by aligning the LZMP to the Actuation Plane, UZMP aligned with neutral axis of the spring.
    b. Principle axes of inertia aligned with desired control system
2. Feedback control is not magic, it will not compensate for sub-optimal system designs. It has fundamental limitations of stability, information, actuator strength, and noise. These limitations restrict the performance of all feedback designs.
3. A system design that permits simple and robust feedback control will be faster, cheaper, require less man-power, and easier to commission, and it will achieve better performance.


## II. List of reasons
1. Good to decouple mechanical dynamics into separate degrees of freedom (DOFs), as close to SISO as you can design
    a. These DOFs should be aligned with a relevant coordinate system, such as parallel and perpendicular to the interferometer (IFO) global control basis.
    b. Each DOF is controllable with simple SISO control. MIMO is difficult to understand, model, and tune. It may also be less robust. Thus, a system that requires MIMO from the beginning is less likely to perform as well.
    c. Control design effort can be focused on those DOFs that require the best performance.
    d. Lesson learned from quadruple suspension: the principal axes of 'pitch' rotation in 2 of the stages are rotated 10 degrees from IFO coordinate system. This causes large coupling between the 'pitch' and 'roll' dynamics. Not only does this make feedback stability more challenging, but more control loops need high performance tuning because they are sensed by the IFO.
2. Strategic sensor and actuator locations
    a. Observe-ability and controllability, i.e. sensors and actuators, have access to relevant dynamics. Can't control what you can't see or drive.
    b. Instrument / Sensor noise can limit where they can go on the mechanical system, e.g. inertial sensors are useless on the quadruple suspension because the suspension is quieter than any reasonable sensor.
    c. Hierarchical control may be needed – big noisy control signals for large displacements closer to the ground, small quiet signals for small displacements closer to the test mass. The mechanical design and

actuator system design must reflect which of these signals go where. Thus, some idea of the control system is needed when the mechanics and electronics are designed.

    d. A good design goal is to have no phase loss between sensor and actuator. This can be achieved with co-locating the sensor and actuators; good structural attachment of sensors and actuators is necessary for the lack of phase loss.

3. Make sure relevant dynamics of the suspension chain (the plant) couple to the sensor and actuator system (if you don't have great sensors or actuators, change the dynamics of the plant so that desired dynamical modes that you wish to control are visible)

    a. Dynamical modes that require control are observable/controllable to control system.

    b. Example: suspension dynamical modes couple to the top mass (where local feedback control system lies) so they can be damped where sensor noise is less of an issue at the test mass because of the passive isolation between those stages.

4. Avoid parasitic vibrational modes

    a. Use a stiff design to push mode frequencies far out of the control band. Low frequency modes limit control bandwidth and stability.

    b. Use passive damping to limit Qs, e.g. Viton.

    c. Mode shapes designed to be invisible to sensors/actuators

5. Big separation of fundamental modes and rigid body modes provides a region to roll off control authority

6. Be conscious of payload actuation interactions with the seismic system

7. Control system doesn't need to be robust against fast payload actuation (think fast, hardware protection shutters), one just needs to be able to recover performance quickly.

Open Questions:

1. Do you need to control every degree of freedom?

2. Eddy current damping – a blessing or a curse?

3. Super attenuators are designed to meet ET requirements. If you're limited by infrastructure – can you just take out a few stages?