# Technical Comments

## Comment on "A Comparison of Control Techniques for Large Flexible Systems"

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THE paper by L. Meirovitch, H. Baruh, and H. Öz[1] compares "coupled control" and "Independent Modal-Space Control" (IMSC). Coupled control refers to modern control in general, and IMSC refers to a control method used when the number of control inputs is equal to the number of controlled modes which controls the modes while keeping them decoupled. The purposes of this comment are 1) to show that many of the conclusions reached by the above authors are incorrect, and 2) to point our some of the engineering limitations of IMSC.

The erroneous conclusions are fairly numerous, and will be examined one at a time.

1) On page 305 of Ref. 1, it is alleged that "...the IMSC method is found to be superior to coupled control when the pole allocation technique is used."

Although some pole placement techniques do have substantial limitations, the qualitative arguments given for the superiority of IMSC over other pole allocation techniques only deal with the simplicity with which pole placment can be carried out using IMSC. Pole placement with multiple inputs is possible, even for those less than trivial cases where the number of actuators is not equal to the number of modes. Pole-placement using the generalized control canonical form (GCCF) is not unduly restrive, as stated in Ref. 1. In fact, the system eigenvectors can also be placed to a certain extent using the GCCF whereas IMSC restricts the closed-loop eigenvectors to be equal to the open loop eigenvectors.

2) On page 306 of Ref. 1, Meirovitch et al. attempt to design an optimal regulator by choosing a state weighting matrix $Q$ whose diagonal elements correspond to the squares of the natural frequencies. They then state that there are no guidelines for the choice of the control weighting matrix $R_I$ and that certain choices may not have physical meaning.

Most optimal regulator designers are much more comfortable with the selection and motivation of the control weighting matrix than with the choice of state weighting matrix. Meirovitch et al. offer no justification for their "logical" choice of state weighting matrix, and indeed, any rigid body modes ($\omega=0$) would not contribute to the cost function for that choice.

3) Later on the same page, the authors write: "For multi-input, multi-output systems, one would have to use switching surfaces in the phase space, which is not possible (reference cited). Hence on-off control in coupled form is virtually impossible."

This statement ignores work which is currently going on in the area of on-off control of flexible structures[2] and also the work that is being done on advanced shuttle autopilots. One of the main motivations for designing on-off control systems, namely the fact that most thruster jets are not throttleable, is also ignored. Declaring as virtually impossible on-off control in coupled form does not bode well for future missions where on-off jets will be used.

4) On page 307 of Ref. 1, it is stated that "the IMSC method leads to a global minimum for the energy, and the actuator locations are immaterial as far as the controlled modes are concerned."

This is a perpetual claim of the proponents of IMSC. It is based on the fact that no matter where actuators are placed, the amount of work done by those actuators to bring the controlled modes to rest is equal to the initial amount of energy in those modes. By virtue of the fact that the work done by the external forces is a path-independent integral (in a conservative system), the work done by the actuators on the controlled modes in bringing them to rest is independent of the number of actuators and their locations regardless of the control method used, not just in the case of IMSC as stated.

The placement of control actuators is important because control effort rather than work affects the cost of the system. As a simple example, consider the optimal placement of a human being (the actuator) on a lever placed on a fulcrum for the purpose of lifting a load. The further out along the lever the human pushes, the less the force he has to generate, but the work needed to lift the load is constant. Similarly, actuators are placed on devices so that the actuator forces required to control the device are minimized. As the weight and cost of actuators is closely related to their peak force capabilities, maximizing the mechanical advantage the authors have is a very important part of the design process.[3]

5) Two paragraphs later, the authors write: "When the IMSC method is used, the performance index $J$ is independent of the actuator locations."

The IMSC method involves a cost function of a very particular form. This cost function automatically adjusts itself so that changes in actuator locations do not cause changes in cost. It has already been pointed out that actuator locations are very important: defining a cost function which ignores the effects of actuator location automatically obscures any beneficial or harmful effects which result from changes in actuator locations.

6) In the next paragraph, the advantages of IMSC are summarized. Those advantages which relate to the relative simplicity of IMSC will not be disputed as it is indeed a very simple control approach. However, objections will be made to points 1, 4, and 7.

Point 1 states that IMSC gives a larger choice of control techniques including nonlinear control. Since it explicitly involves a linear transformation of the control vector, IMSC by its very form will never be able to handle true on/off actuators. "Nonlinear" describes only the internals of the control algorithm itself. Given that linear control algorithms invariably outperform nonlinear algorithms when linear actuators are available, there are very few reasons to go to a nonlinear control algorithm if a linear one is implementable, and many reasons not to.

Point 4 implies that IMSC is "more" implementable in microprocessor-based control systems. The formulation of IMSC does not reduce the number of computations that must be carried out by a control system in real time. In IMSC, each "modal" control only depends on two states, modal amplitude and velocity, whereas in coupled control, each control depends on every state. However, the IMSC "modal" controls must still be transformed into real-space controls, so that the number of real-time arithmetic operations required for

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each is the same. IMSC only reduces the number of computations that must be carried out during the design process.

Point 7 states that IMSC uses less energy. We must distinguish between vibrational energy in the structure and energy used by the actuators in producing work. As stated earlier, the relationship between changes in vibration energy and work is independent of the control method used. However, since different actuators can have different efficiencies and different mechanical advantages, to minimize the power (or over time, energy) used by the actuators, we should use efficient (or low-cost) actuators which have good mechanical advantage more than inefficient actuators with poor mechanical advantage. Since IMSC never concerns itself with the energy going into the actuators, only the work going into the controlled modes, it is highly unlikely that IMSC would produce a minimum energy design in the sense of squared actuator effort or energy used by the actuators.

7) A numerical example is given which illustrates the advantages of IMSC. In all cases, the control system performs better when more actuators are available.

It is important to note that when quadratic performance indices are used, additional actuators will always reduce costs in a control problem in duality with the way that additional sensors always reduce uncertainty in an estimator problem (no matter how poor they are!). It is thus not unexpected that in examples where IMSC has more actuators available to it than other methods, IMSC will always appear better.

8) When costs are compared in the numerical example, the cost function used is always the one for which IMSC is optimal.

It seems meaningless to compare two control approaches if the performance index used for comparison is always exactly minimized by one of the approaches. This is like comparing apples and oranges on the criteria of which one is more "orange-like." Some "real-world" performance criteria must be used. IMSC would certainly fare very poorly if a term which was a function of the number of actuators (increased number of actuators = increased complexity and cost) was included in the cost function.

Additional practical problems exist with the IMSC method. These could be ignored if one were dealing with a purely theoretical problem, but IMSC is sold as a solution to a real problem.

1) The number of actuators must equal the number of modes.

With this constraint, the possibility of actuator failures becomes a critical problem. Must each actuator be backed up directly or must spare actuators at other locations be brought on line? Furthermore, what happens if the number of controlled modes must be increased during flight? Must spare actuators be available for this sort of contingency?

2) When IMSC is used, the $B$ matrix (Meirovitch's notation) must be nonsingular.

What if the $B$ matrix is nearly singular? IMSC could end up demanding nearly infinite forces from the real actuators.

3) An IMSC controller cannot be tailored to available actuators.

Mission requirements other than vibration control may produce actuator configurations incompatible with IMSC in that the actuators cannot provide the relative force distribution IMSC demands.

On a fundamental level, control systems are designed to control the outputs of the physical plant using the inputs so that certain performance specifications (which are functions of the outputs) are met. Modal equations of motion are merely a mathematical representation (an approximation, in fact) of the internal behavior of the system. The modal amplitudes and rates are thus internal (and even scaleable) variables which are only important insofar as they affect the system outputs. Keeping the internal variables decoupled through IMSC may seriously hamper efforts to control the system outputs.

## References

[1] Meirovitch, L., Baruh, H., and Öz., H., "A Comparison of Control Techniques for Large Flexible Systems," *Journal of Guidance, Control, and Dynamics*, Vol. 6, July-Aug. 1983, pp. 302-310.

[2] Vander Velde, W.E. and He, J., "Design of Space Structures Using On-Off Thrusters," *Journal of Guidance, Control, and Dynamics*, Vol. 6, Jan.-Feb. 1983, pp. 53-60.

[3] Longman, R.W. and Alfriend, K.T., "Actuator Placement from Degree of Controllability Criteria for Regular Slewing of Flexible Spacecraft," IAF Paper No. 79-95, 30th Congress of the International Astronautical Federation, Munich, Germany, Sept. 16-22, 1979.

# Comment on "A Comparison of Control Techniques for Large Flexible Systems"

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IN Ref. 1, Meirovitch, Baruh, and Öz present a comparison of control system design techniques for the regulation of large flexible systems. They choose to approach the effort by grouping several quite distinct multivariable design methods under the heading "coupled controls," and then comparing them with their own technique, known as independent modal-space control (IMSC). The comparison is made on three fronts, namely 1) pole allocation, 2) linear optimal control, and 3) nonlinear on-off control. A discussion of control implementation considerations is followed by a numerical example. The authors summarize eight advantages of IMSC and yet find only one advantage among all the "coupled controls" techniques considered (namely, that the designer is not restricted, as in IMSC, to require as many actuators as there are modes in the linear system model).

Here, reexamination of the authors' three specific comparisons and further comments on control implementation will bring to light several disadvantages of IMSC which clearly temper the conclusions presented in the original work.

## Pole Allocation

In discussing the various techniques for arbitrary eigenvalue assignment via state feedback, the authors point out that for multi-input systems the problem is underdetermined. That is, in general there exist many feedback gain matrices which will achieve the desired closed-loop pole placement. The remaining design freedom is used in the various techniques to achieve additional closed-loop system characteristics, for example, to obtain prescribed gain or minimum gain controllers.[2] Through conversion to a scalar input system, Kailath[3] demonstrates that all eigenvalues may be arbitrarily placed by specification of a single input, and that the remaining freedom may be used to achieve closed-loop eigenvector assignment as well.

In contrast, the IMSC method of pole placement, in addition to requiring $n$ inputs for a $2n$-dimensional system, uses all available design freedom to achieve the desired closed-loop poles alone, and no freedom exists to specify other closed-loop system characteristics. Based on computational simplicity, the authors view IMSC as a superior approach.

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