N92-27724

LARGE-GAP MAGNETIC SUSPENSION SYSTEMS

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SUMMARY

This paper will address the classification of magnetic suspension devices into small-gap and large-gap categories. The relative problems of position sensing, control systems, power supplies, electromagnets and magnetic field or force analysis will be discussed. The similarity of all systems from a controls standpoint will be qualified. Some applications where "large-gap" technology is being applied to systems with a physically small air-gap will be mentioned. Finally, the applicability of some other suspension approaches, such as electrodynamic or superconducting, will be addressed briefly.

INTRODUCTION

The majority of research concerning magnetic suspension devices has concentrated on systems and applications where the air-gap between suspended object and suspension elements has been relatively small. This has been especially true in recent years, with the strong growth of interest in, and application of, magnetic bearings. In turn, the predominant technical approach used to date for bearings has been the feedback-controlled electromagnet/ferromagnetic suspended element type. There are applications, however, where large air-gaps are essential; perhaps the longest-standing of these being Magnetic Suspension and Balance Systems for wind-tunnel models (MSBS) and magnetically-levitated trains (Maglev), both illustrated in Figure 1. Other applications are now emerging where large-gap systems are of interest or where the design approaches used in large-gap systems are applicable. Some examples of these applications are multi-degree-of-freedom microgravity vibration isolation and large-angle space-based gimballing and pointing systems, illustrated in Figure 2. From a controls standpoint, the large- and small-gap systems prove to be quite similar, but in most other respects can be dramatically different.

FIELDS AND FORCES

This section will start with some simple analysis of small-gap systems, leading to consideration of larger-gaps, highlighting some of the important trends involved. Small-gap systems are frequently designed, at least in the preliminary stages, using magnetic circuit theory. A sketch of a representative two-pole suspension system is shown in Figure 3. The important features are the uniform air-gap, and the presence of iron yokes and/or back-iron. Examining the magnetic circuit, it is clear that the reluctance of the circuit is dominated by the air-gap, which is, in turn, the parameter being controlled. Using standard formulations, chiefly :

$$\frac{F}{A} = \frac{B^2}{2\,\mu_0} \qquad - (1)$$

- it is easily shown that:

$$F = \frac{\mu_o\, A\, (NI)^2}{4\, h^2} \qquad - (2)$$

A fringing factor is usually introduced to account for flux non-uniformity but is not necessary here. The total flux linking the coil is :

$$\phi = \frac{\mu_o\, (NI)\, A}{2\, h} \quad \propto \frac{1}{h} \qquad - (3)$$

The stored energy in the system can be calculated from :

$$E = \frac{B^2}{2\,\mu_o} * \mathrm{Vol} \qquad - (4)$$

- where this expression is appropriate for linear material characteristics and is only large in the air region for this problem. The energy/force ratio is important and is found to be (see also Figure 4) :

$$\frac{E}{F} = h \qquad - (5)$$

It is now argued that this is a crucial factor distinguishing small-gap and large-gap systems. Large-gap systems involve considerable stored energy, tending to lead to large, highly stressed electromagnets and large, expensive power supplies. Typically, the natural frequencies of the suspension system will tend to be reduced, principally due to the associated high inductance of the electromagnets, since :

$$E = \frac{1}{2}\, L\, I^2 \qquad - (6)$$

Continuing with classical analysis and following established magnetic bearing terminology, the position and current stiffnesses can be found by differentiation of equation (2) :

$$K_x = -\left.\frac{\partial F_y}{\partial x}\right)_o = -\frac{\mu_o\, A\, (NI)^2}{2\, h^3} \qquad - (7)$$

$$K_I = \left.\frac{\partial F}{\partial I}\right)_o = \frac{\mu_o\, A\, N^2\, I}{2\, h^2} \qquad - (8)$$

It is seen that the position stiffness is completely determined by the geometric configuration and is independent of the coil design. The current stiffness of course depends on the choice of the number of turns in the coil. Additional practical details include the effective magnetic "pressure" in the air-gap, found to be approximately 1 atmosphere for B=0.5T, using (1). It is clear from (1-4) that the efficient transmission of large forces requires a small air-gap and large pole face area. It is also clear that this simple suspension configuration exhibits severe non-linearities with respect to gap and current.

In large-gap systems it is a practical impossibility to generate uniform flux penetrating the suspended object. The simple formulae shown above are therefore not applicable, though several options are available. First, it is recognized that (1) is merely the normal component of Maxwell stress. For large-gap systems, the Maxwell stresses on arbitrary surfaces completely enclosing the suspended object can be integrated to yield the total force (and moment) on the object [1], but normal and shear stresses must both be considered:

$$\vec{F} = \frac{1}{\mu_o} \int_S T_{ij} \cdot d\vec{S} \qquad \text{where } T_{ij} = \begin{bmatrix} (B_x^2 - \frac{1}{2}|B|^2) & B_xB_y & B_xB_z \\ B_xB_y & (B_y^2 - \frac{1}{2}|B|^2) & B_yB_z \\ B_xB_z & B_yB_z & (B_z^2 - \frac{1}{2}|B|^2) \end{bmatrix} \qquad - (8)$$

The terms on the leading diagonal of the stress tensor, T_{ij} are recognized as constituting the $\frac{B^2}{2\mu_o}$ term which in turn leads to the form of (1). Alternatively one may use :

$$\vec{F} = \int_V (\vec{M} \cdot \nabla)\vec{B}\, dV \quad \text{and} \quad \vec{T} = \int_V (\vec{M} \times \vec{B})\, dV \qquad - (9)$$

The latter forms may be quite convenient for permanent magnet suspended elements and are usable, though inconvenient, for soft-iron elements. In this application, $\vec{B}$ in equation 9 may be taken as the "external" or applied field; the field that would exist if the magnetization of the suspended element were removed from the problem. This is easily calculated in the case of permanent magnet suspended elements, slightly more difficult for soft-iron, provided that there is negligable magnetization of suspension electromagnet cores by the suspended element. This is only likely to be the case with large-gap systems.

It should be clear that field gradients are the key factors in the production of forces, either directly through the $\nabla\vec{B}$ term in (9) or indirectly via integration over the closed surface in (8). It can be noted that a gradient exists in Figure 1, due to the reversal in sign of flux relative to the suspended object. That is, entering on one side and leaving on the other, although the magnitude of the flux is relatively uniform in the region of each pole face.

No simple formula exists for "position stiffness", due to the presence of numerous field and field gradient terms. Previous work [2,3] has resulted in linearized models for suspended permanent magnet elements under certain restrictive conditions, from which current and position stiffnesses can be found. As a point of interest, if the suspended object has a permanent magnet core then the current stiffness can be deduced directly:

$$K_i = \frac{F_o}{I_o}$$

SOME ASPECTS of the TECHNICAL DEVELOPMENT of WIND TUNNEL MSBSs

With the local air-gap as the controlled variable in small-gap systems, each suspension station becomes a quasi-one-degree-of-freedom subsystem. With a rotor, for example, a minimum of five bearings would be needed for full control, typically a vertical and horizontal bearing at each end of the shaft, plus a single axial "thrust" bearing. This arrangement facilitates relatively straightforward decoupling between degrees-of-freedom. Extra complications do arise due to geometrical or mass asymmetries and due to structural flexibility, and are the subject of considerable research. Many microgravity or vibration isolation systems have been designed with this "built-in" decoupling.

The earliest, widespread application of large-gap suspension was to wind tunnel MSBSs. There is evidence that the early thinking with MSBSs was consistent with the point actuator viewpoint. For instance see Figure 5 [4,5], where the suspension systems are seen to resemble a bearing supported shaft. Further, many early MSBS control systems were configured so that the current in each electromagnet was controlled on the basis of the distance of the model from that electromagnet, i.e. the local airgap, just as in the magnetic bearing case. As the complexity of systems increased, and as the geometry of the suspended object became less like that of a slender shaft, this approach failed. MSBSs developed in the early to mid-1960s were generally based on "coupled" control systems, that is sensors were placed wherever convenient, signals were mixed to sensible degrees-of-freedom (usually the principal axes of the suspended element) with a distribution network to allocate control demand among suitable electromagnets. An alternative interpretation is a double coordinate transformation, from sensor axes to object axes, then from suspended object axes to electromagnet axes. This inevitably leads to the development of an entirely different set of governing equations, based directly on field and field gradient components in space, rather than point forces, as discussed earlier.

The next phase of development of design approaches is represented by the MIT 6-inch system, illustrated in Figure 6, where considerable efforts were made to ensure that separate field and field gradient components were generated independently, and also with good spatial uniformity, by separate sets of electromagnets [6]. Each of these sets was then wired in series and fed from an individual power supply. This again provides for controller decoupling, albeit in suspended object axes rather than MSBS axes, and considerably simplifies the force calibration, but has some disadvantages. Notably the maximum force capability of the electromagnet assembly cannot be realised, since individual electromagnets cannot be run up to their respective current limits independently, as shown in Figure 7.

Contemporary thinking is therefore to distribute an array of general-purpose electromagnets around the wind tunnel test section and operate each independently. This will provide the maximum possible force and moment capability at all attitudes, but can lead to complex calibration procedures; still a subject of considerable research [7].

SCALING of MAGNETIC SUSPENSION SYSTEMS

The subject of scaling laws has been addressed previously [8,9]. It is found that in many systems, where a limit to the maximum field intensity exists and is important (such as a superconductor critical field, permanent magnet coercive field and so on), scale such that the magnetic force varies as length squared, rather than as the volume of magnetic material as is often assumed. Relevant to previous discussions, the system stored energy will then scale as length cubed, leading to the expected result -

$$\left.\frac{\text{Stored energy}}{\text{Force}}\right|_{\text{Max. field limited}} \propto \frac{L^3}{L^2} \propto L \propto \text{Air-gap}$$

CONTROL and RELATED PROBLEMS

In large-gap systems the number of "actuators" (controlled currents) frequently exceeds the number of degrees-of-freedom to be controlled. This results in the equilibrium point (and the control problem in general) being underdetermined, i.e. an infinite set of solutions for suspension currents, more particularly current distribution, exist. This poses two problems, determination of a suitable current distribution to generate the required forces and torques, and the determination of the maximum force and moment capability, such as where hard electromagnet current limits exist.

The first problem can be overcome by physical argument, as used in Reference 7, where a systematic scheme was developed for "allocating" demand in a hierarchical manner, such that the most effective electromagnets took the largest load. Alternatively, matrix theory may be brought to bear in the following manner. If the forces and moments generated by the electromagnet array can be written in the linear form shown :

$$\begin{bmatrix} T_y \\ T_z \\ F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} K_{z_1} & K_{z_2} & K_{z_3} & K_{z_4} & K_{z_5} \\ K_{y_1} & \ddots & & & \\ K_{xx_1} & & \ddots & & \\ K_{xy_1} & & & \ddots & \\ K_{xz_1} & & & & \ddots \end{bmatrix} \begin{bmatrix} I_1 \\ \\ \\ \\ I_5 \end{bmatrix} \qquad - (3)$$

- otherwise written as :

$$A\,I = F$$

- then the problem is to find a pseudoinverse A^{-1} that satisfies sensible physical constraints. The classical pseudoinverse (Moore-Penrose) yields a solution such that the 2-Norm of the solution current vector is minimized.

This corresponds to the minimum sum of squares of electromagnet currents, in other words the minimum power solution for conventionally conducting electromagnets, also the minimum stored energy solution in all cases, though perhaps requiring some scaling in the case of different sized electromagnets. An alternative inverse will give the minimum ∞-Norm, corresponding to the maximum value of an individual current being a minimum, and by inference to the maximum force and moment capability. This is more appropriate in the case of superconducting electromagnets, or where hard current limits are important. A residual problem is that this latter solution has been shown to exhibit discontinuities as a function of some variable, such as suspended object orientation [9].

POSITION (or RATE) SENSING

A wide variety of sensing systems have been used for both small-gap and large-gap systems. Some, chiefly optical systems, are usable at all air-gaps, some are relatively specific to one size gap or the other. For example, commercial capacitive or inductive sensors are only suitable for small gaps. Rather than attempt a comprehensive survey of all techniques, a few technical observations relevant to large-gap systems will be made.

The most common approach used has been the analog optical obscuration approach. The X-ray system used in the AEDC MSBS was conceptually similar [5]. Although this approach is capable of picking off a single motion from one point of a suspended object, multi-degree-of-freedom systems become quite complex (Figure 8), extremely sensitive to detail geometry of the suspended object and prone to couplings between degrees-of-freedom. Nevertheless, the fact that high sensitivity can be achieved easily is a strong positive factor, and the approach remains the first choice for many experimental systems.

A significant refinement is the use of linear scanning photo-diode arrays as the light sensors. This greatly improves system linearity, repeatability and environmental tolerance, but does not overcome other objections mentioned above [10]. The way forward appears to be camera-based sensing, where some form of target is monitored by an array of cameras (presumably solid-state), illustrated in Figure 9. Existing camera technology is already adequate for low-to-medium frame rates, though the image processing requirements are formidable. Processing hardware capable of useful data rates is only just becoming available [11].

OTHER SUSPENSION APPROACHES

This paper has concentrated on the feedback-controlled electromagnet/ferromagnetic suspended element type of system. Numerous alternatives exist, including A.C. or eddy current methods, many variations incorporating diamagnetic material, or permanent magnets in repulsion. More comprehensive treatment and discussion can be found in Reference 12. Many of the alternative approaches could be applied to large-gap systems. However, in the context of the anticipated applications, all alternatives appear to have serious shortcomings.

Notably, in applications involving pointing and manipulation, set-point control is needed, which open-loop suspensions cannot easily provide. In many other applications, such as wind tunnel MSBSs or certain types of vibration isolation, heavy damping of suspended element motion is required. With the stored energy of all types of suspension system rising with increasing air-gap, it is not clear how good motion damping, implying dissipation of large quantities of energy, can be arranged. Further research and development will improve matters, as is clearly the case with the ElectroDynamic Suspension system (EDS), for Maglev trains. This system [13] is, by all resonable measures, a large-gap suspension. That is, air-gap size is not small with respect to system scale.

A FEW FINAL THOUGHTS

The fringing fields generated by large-gap suspension systems are sometimes cited as a serious obstacle to their use in certain applications, perhaps particularly spaced-based applications. The production of powerful fields (possibly time-varying) in the region surrounding the suspension system is certainly a problem, but can be overstated.

It is noted here that since the field sources are essentially dipoles (current-loops or permanent magnets), the magnetic field strength in the far-field will decay at least as the cube of distance. Further, since the net strength of suspension system dipoles is often zero, the decay can be even faster, and the resultant force and torque in uniform external field (such as the earth's field) will be zero.

ACKNOWLEDGEMENTS

This work was partially supported by NASA Grant NAG-1-1056, Technical Monitor Nelson J. Groom.

REFERENCES

1. Lowther, D.A.; Silvester, P.P.: Computer-Aided Design in Magnetics. Springer-Verlag.
2. Groom, N.J.: Analytical Model of a Five Degree-of-Freedom Magnetic Suspension and Positioning System. NASA TM-100671, March 1989.
3. Groom, N.J.; Britcher, C.P.: Stability Considerations for Magnetic Suspension Systems Using Electromagnets Mounted in a Planar Array. NASA CP-10066, March 1991.
4. Moreau, R.: Use of Magnetic Suspension in O.N.E.R.A. Wind Tunnel. In ARL Symposium on Magnetic Wind Tunnel Model Suspension and Balance Systems. Dayton, OH, 1966. ARL-66 -0135, July 1966.

5. Crain, C.D.; Brown, M.D.; Cortner, A.H.: Design and Initial Calibration of a Magnetic Suspension System for Wind Tunnel Models. AEDC-TR-65-187, September 1965. (In abbreviated form in ARL Symposium on Magnetic Wind Tunnel Model Suspension and Balance Systems. Dayton, OH, 1966. ARL-66-0135, July 1966)

6. Stephens, T.: Design, Construction and Evaluation of a Magnetic Suspension and Balance System for Wind Tunnels. MIT-TR-136, NASA CR-66903, November 1969.

7. Parker, D.H.: Techniques for Extreme Attitude Suspension of a Wind Tunnel Model in a Magnetic Suspension and Balance System. NASA CR-181895, October 1989.

8. Zapata, R.N.: Magnetic Suspension for Large-Scale Aerodynamic Testing. In Wind Tunnel Design and Testing Techniques, AGARD CP-174, March 1976.

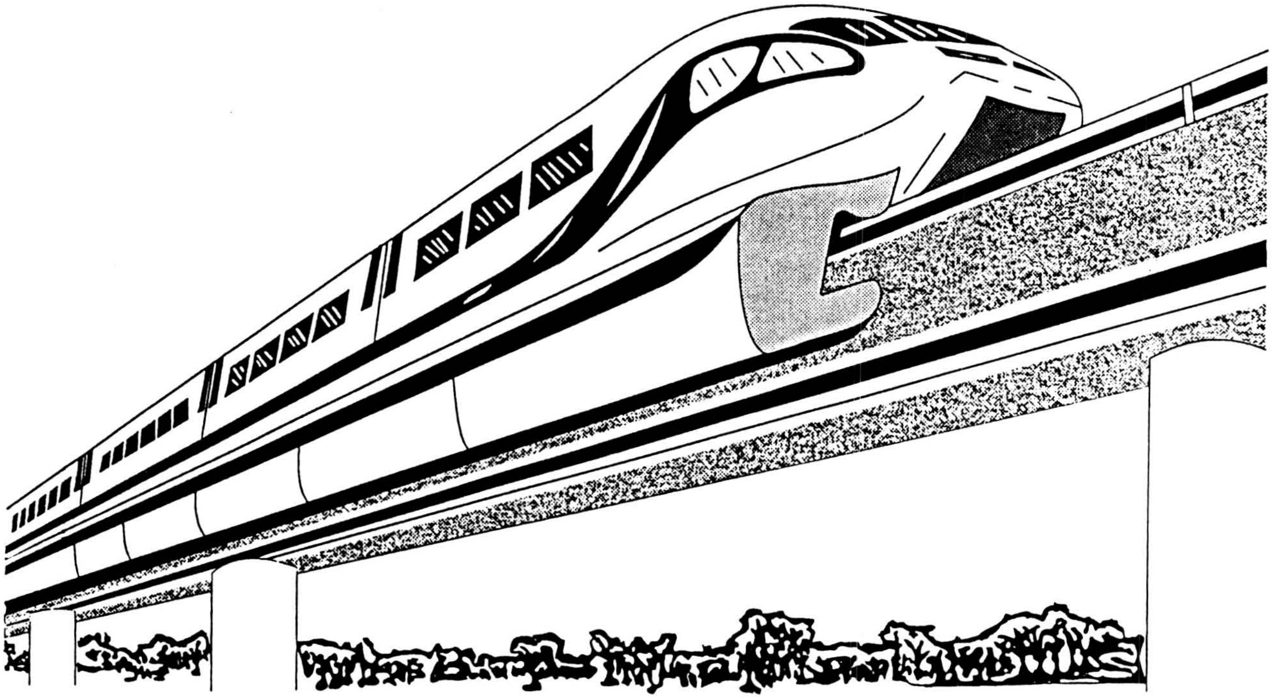
9. Britcher, C.P.: Some Aspects of Wind Tunnel Magnetic Suspension Systems with Special Application at Large Physical Scales. NASA CR-172154, September 1983.

10. Schott, T.D.; Tcheng, P.: The New Electro-Optical Displacement Measuring System for the 13-inch MSBS. In NASA Workshop on Aerospace Applications of Magnetic Suspension Technology, NASA CP-10066, March 1991.

11. Welch, S.S.; Clemmons, J.I.; The Optical Position Measurement System for a Large-Gap Suspension System. In NASA Workshop on Aerospace Applications of Magnetic Suspension Technology, NASA CP-10066, March 1991.

12. Jayawant, B.V.: Electromagnetic Levitation and Suspension Techniques. Edward Arnold, 1981.

13. Society of Automotive Engineers. Magnetic Levitation Technology and Transportation Strategies. SAE SP-834, August 1991.



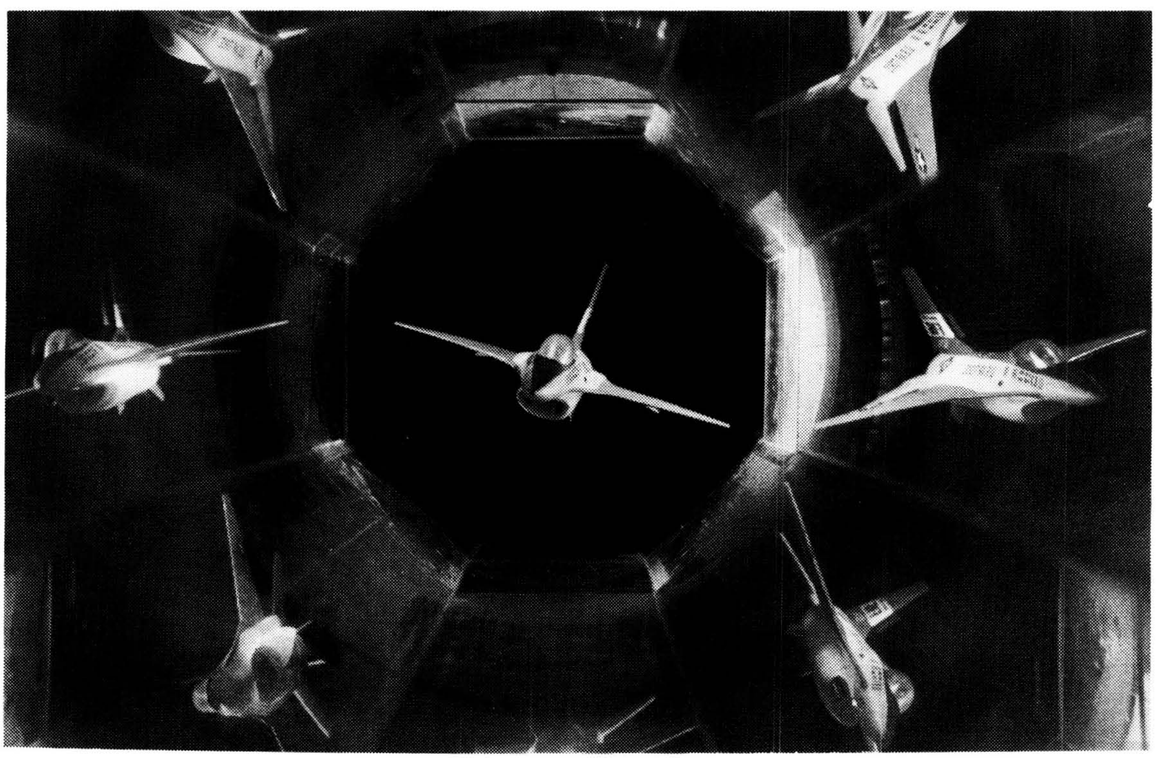
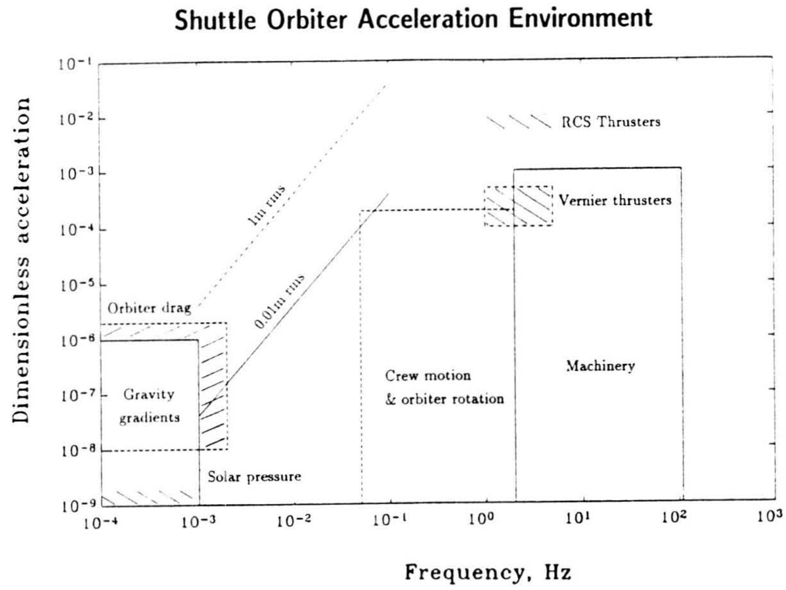


Figure 1 - Established Applications for Large-Gap Magnetic Suspensions

- Maglev and wind tunnel MSBSs



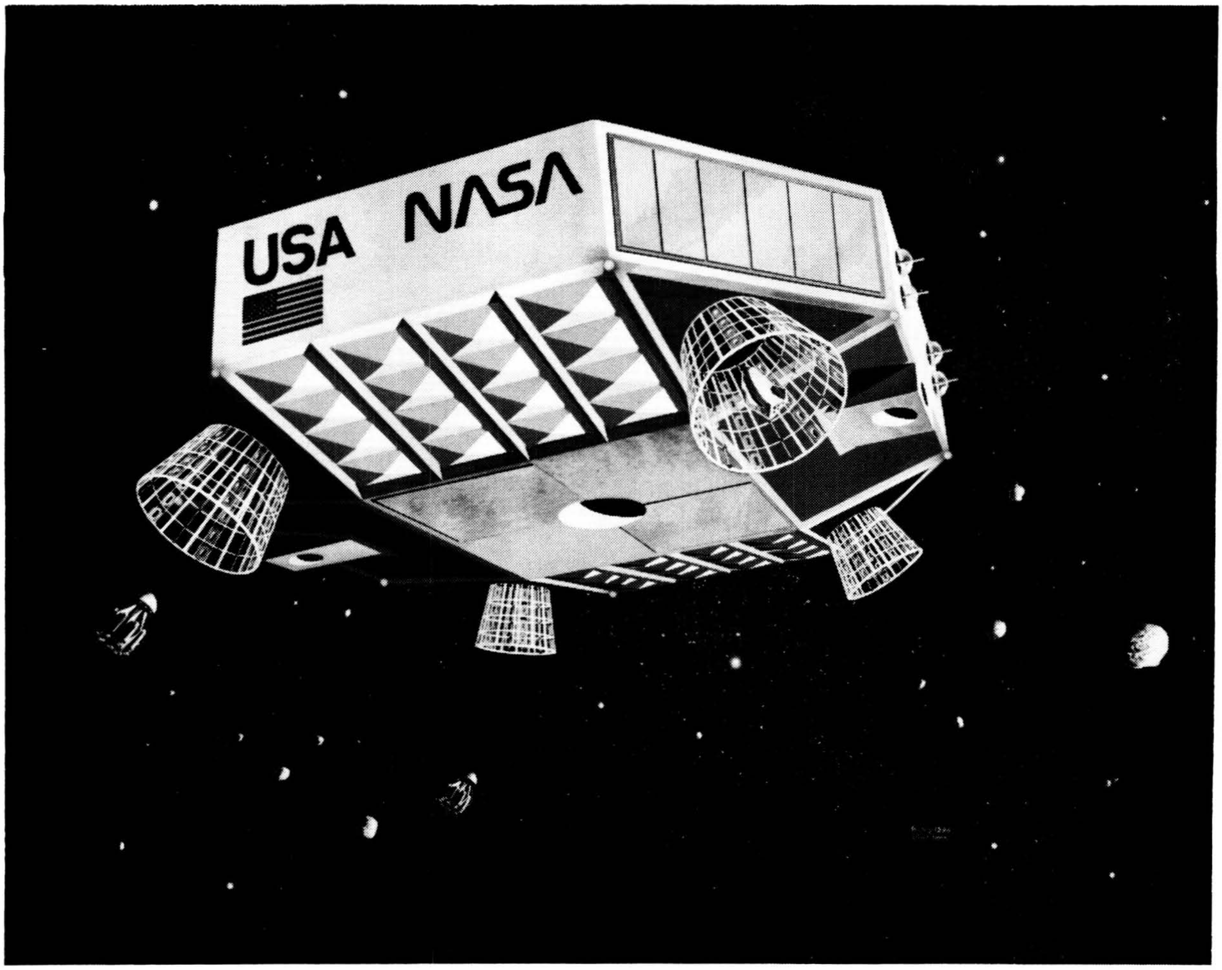


Figure 2 - Potential Applications for Large-Gap Magnetic Suspensions

- low frequency microgravity isolation, space-based pointing or payload manipulation

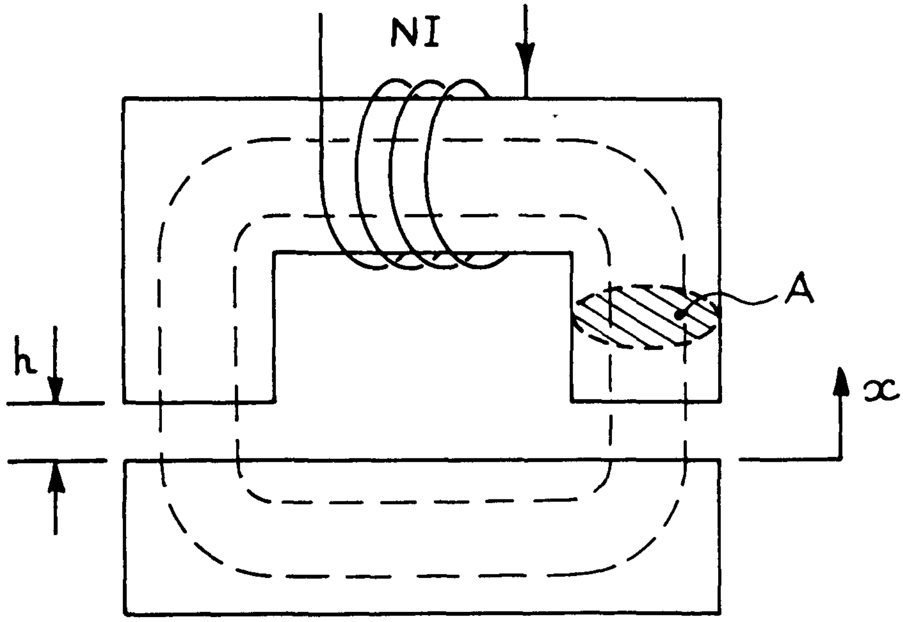


Figure 3 - Schematic Diagram of a 2-Pole Small-Gap Suspension

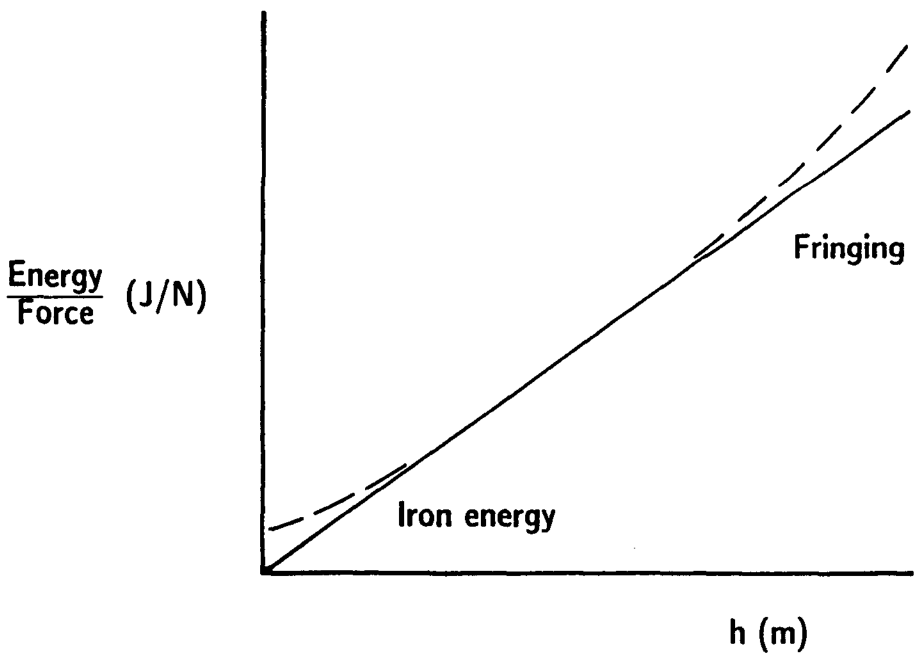


Figure 4 - Energy/Force Relation for a 2-Pole Small-Gap Suspension

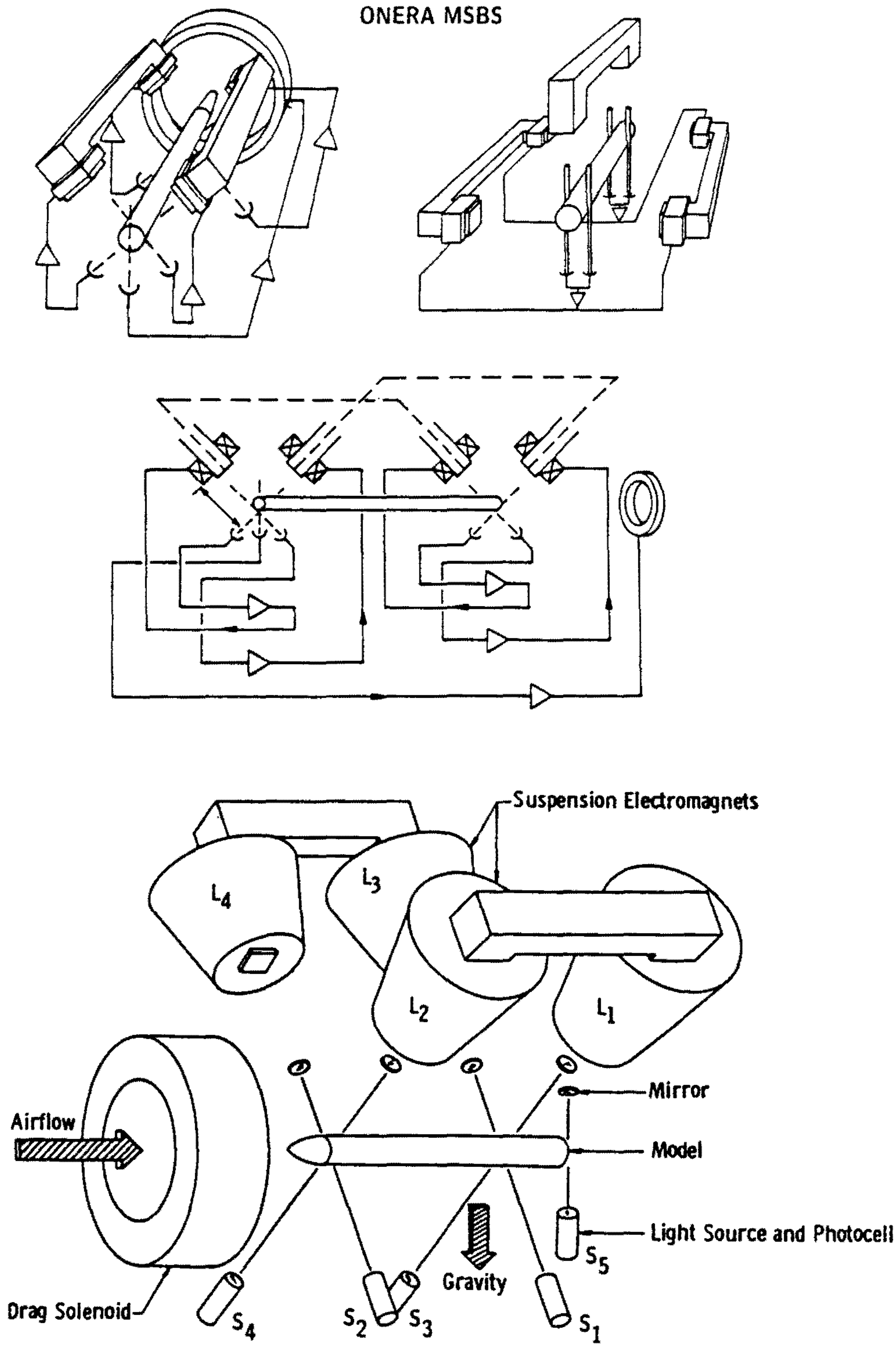


Figure 5 - Design Details of Early MSBSs

- ONERA and AEDC

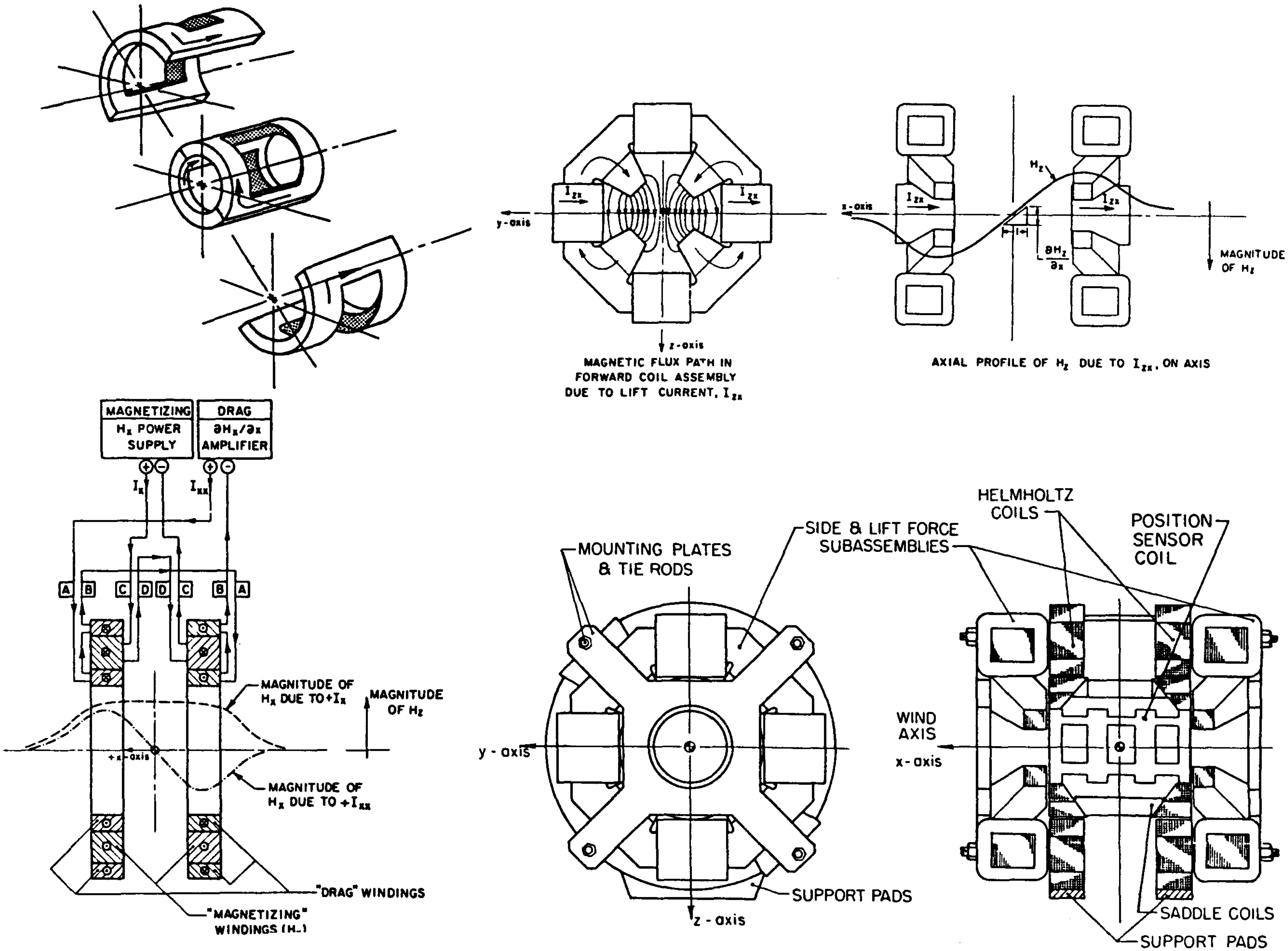


Figure 6 - Magnetic Configuration of the MIT 6-inch MSBS

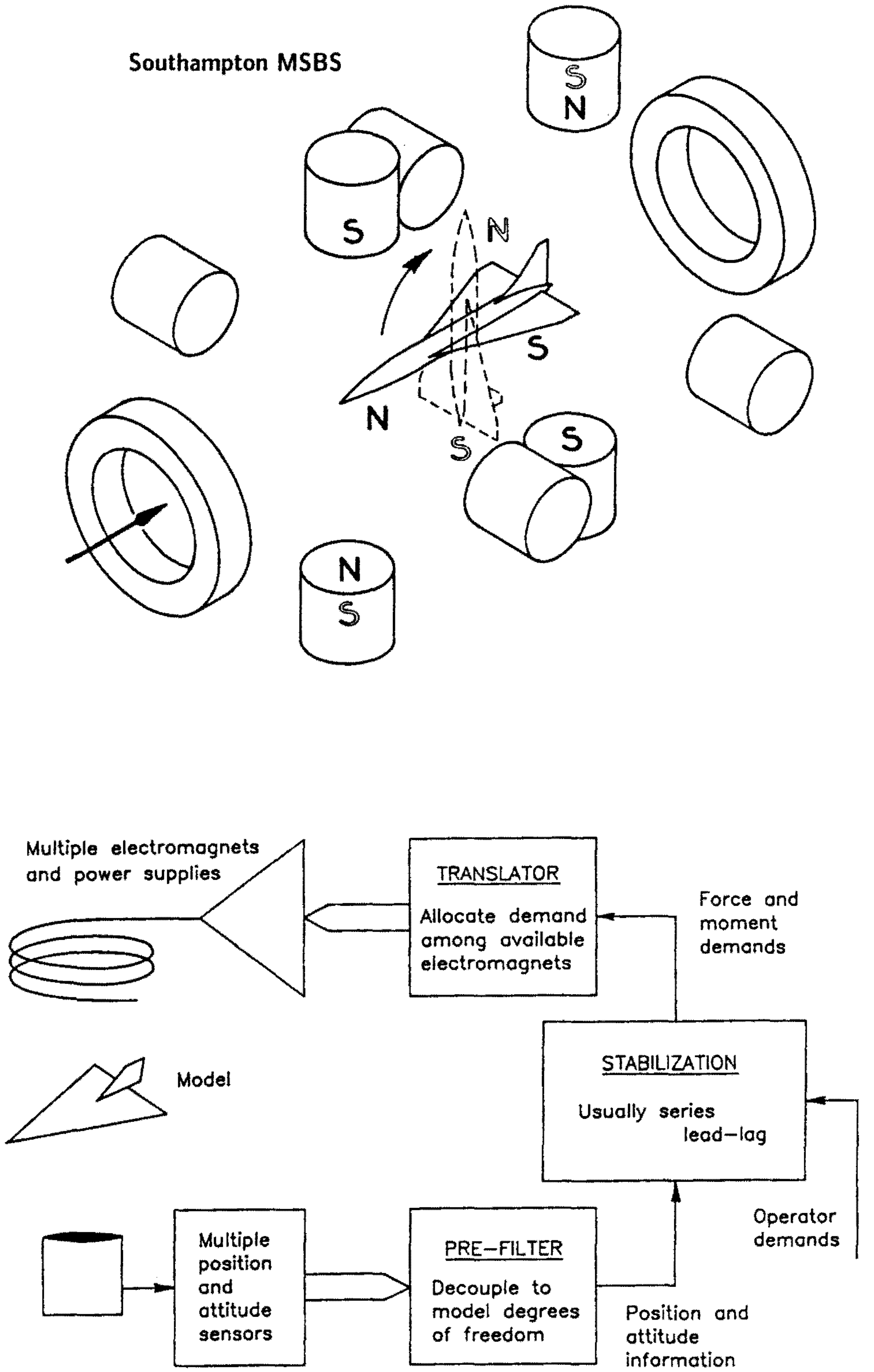


Figure 7 - Example of Contemporary Thinking Regarding MSBS Configuration

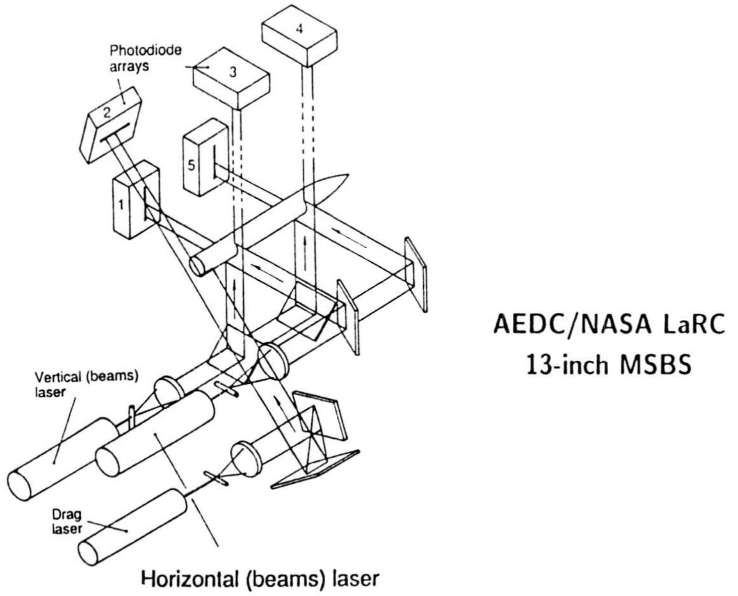


Figure 8 - Layout of Optical Position Sensing System for NASA 13-inch MSBS

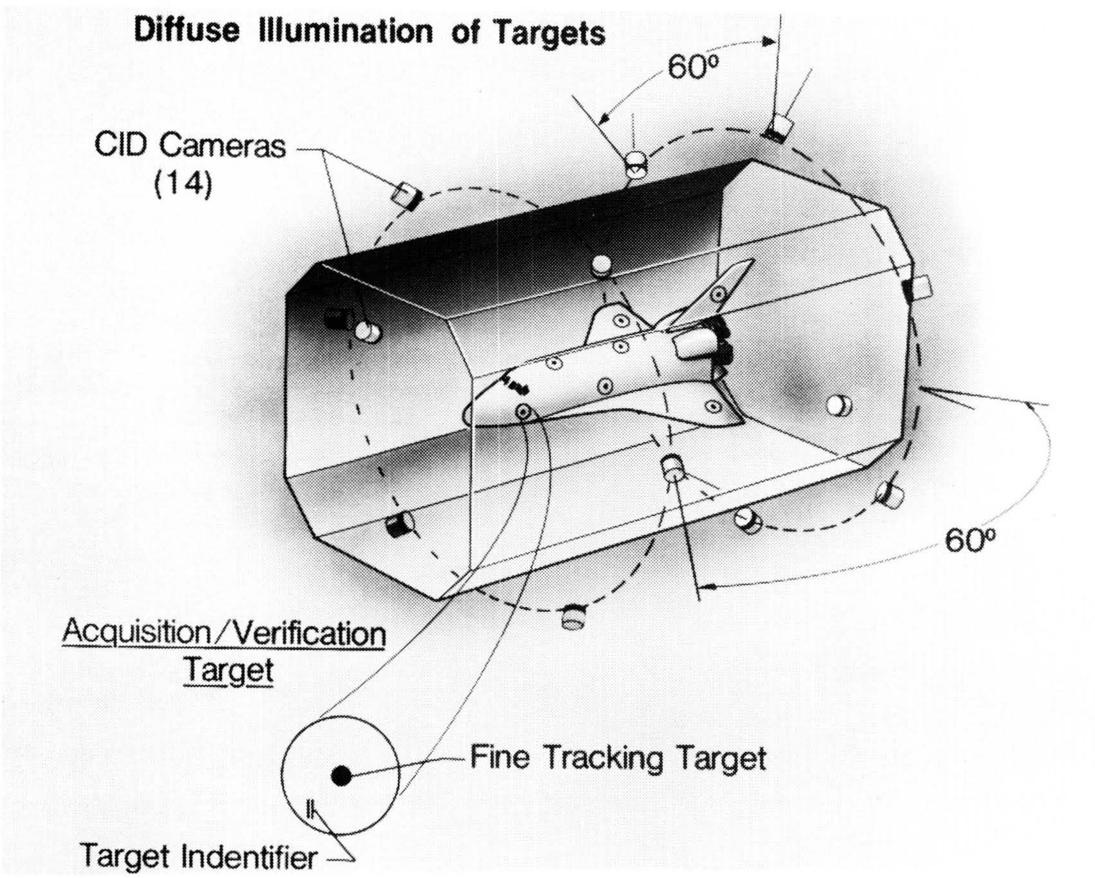


Figure 9 - Conceptual Layout of Advanced Optical Position Sensing System