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Impact of optics design decisions upon line-of-sight stabilization

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Abstract

The process of designing line-of-sight stabilization systems is an interdisciplinary process that requires interaction of mechanical engineers, electronics designers, and servo analysts as well as the optics engineer. The decisions made by the optics designer can have a significant impact upon the final system configuration and performance that is achieved. The stabilization mechanism must support the optical package, must not obstruct the line-of-sight, and must be balanced in order to achieve the desired degree of inertial stabilization. This paper defines the common approaches used to achieve line-of-sight stabilization and discusses the design process that is followed as stabilization systems are conceived and fabricated. Attention is then given to the impact of some of the decisions made by the optics designer and the resultant constraints that are imposed upon the stabilization design by these choices.

Introduction

Whenever an optical system is to be integrated into a movable vehicle, there are many design disciplines that must interact to produce the complete system. The optical system ....using the term in a broad sense to encompass detectors, coolers, electronics, scanning mechanisms, etc....is the key element. The optical system is the "payload", the "brains", and the reason for being. Because of this key role that the optical systems plays, it is not suprising that the decisions made when designing the optics have a critical impact on virtually all other subsystems. One such subsystem is the inertial line-of-sight (LOS) stabilization mechanism. The objective of this paper is to explore some of the ripple effects that the optics design have on the LOS stabilization system. Hopefully, these considerations will identify areas within the optical design tasks where tradeoffs could be made and thereby achieve improved performance in the final integrated system. To lay the foundation for these considerations, let us first review inertial stabilization systems in general, and two of the common stabilization techniques in particular. Then we shall outline the process by which LOS stabilization systems are designed which will lead to some specific optical issues which impact the stabilization design. As we have written this article, we have tried to answer the question, "What would a stabilization designer want to tell his peers within the optical design areas?"

Inertial stabilization systems

A stabilized platform is an electro-mechanical subsystem designed primarily to isolate a "load" from its environment. The payload might be a forward looking infrared receiver (FLIR), T.V. camera, laser designator, missile seeker, or other active element. The environment is determined by the motion of the aircraft, missile, ship, or land vehicle which carries the load. The second objective of a stabilized platform is to "point" the payload in a given direction as it is operated in its environment. Therefore the stabilization system is a mechanical interface between the sensor payload and the vehicle which carries the payload. As such, it consists of (1) a mechanism which enables the payload LOS orientation to be altered with respect to the vehicle's orientation and (2) a means for manipulating the mechanism so that the LOS is controlled in some desired manner.

The most common general design approaches for achieving LOS stabilization for optical sensors are direct mass stabilization, mirror stabilization, and momentum wheels. Momentum wheels are more restricted in their applications than the other two. Mass stabilization refers to the situation where the entire optical sensor is stabilized in inertial space by being supported by a gimbal assembly (Figure 1). Mirror stabilization is the technique whereby LOS is controlled by altering the orientation of a reflective element within the optical path between the body-fixed sensor and the intended target. (The mirror is supported by a gimbal assembly). There are several advantages and limitations of these approaches relative to each other. The key difference is the optical doubling that occurs

MASS STABILIZATION

MIRROR STABILIZATION

Figure 1. Common stabilization techniques

with the mirror system and the generally smaller mass and inertia that must be controlled. In order to achieve stabilization, optical doubling requires mirror movement in inertial space at one half that of the LOS. Therefore the natural stabilization tendency, as reflected by Newton's laws, can not be used in the mirror stabilization system unless some type auxilary mechanism, such as inertial balancers, are employed.

Regardless of whether the system is a mirror or a complete optical system, the technique by which the stabilization mechanism is manipulated can be generalized into a block diagram similar to Figure 2. The key element for the "stabilization loop" is the inertial sensor which responds to the movements of the stabilization mechanism in inertial space and produces an output that is directly proportional to its inertial motion. The inertial sensor frequently selected is a gyroscope which measures rotational motion since the primary movement of the gimbal assembly is rotational in nature. There is a wide variety of gyro-type devices available with corresponding trade-offs between cost and overall precision of performance.

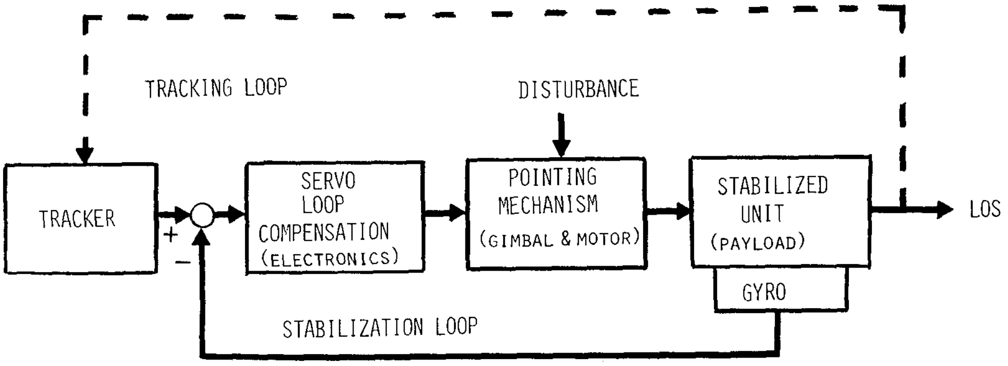

Figure 2. Generalized block diagram of stabilization systems

The output of the inertial sensor "measurement" is used as a negative feedback signal to generate a command in the stabilization loop to null the inertial motion. The compensation electronics are necessary to insure stability of the feedback system and to achieve the desired response characteristics of the overall system.

If the stabilization loop were perfect, then the inertial sensor would sense all inertial movement and the loop would compensate completely so that the gimbal mechanism would be "locked" into its inertial orientation. All external disturbances would be sensed and corrected. However, no loop can be perfect and, furthermore, disturbance isolation is not the total objective of the stabilization system....it must also be able to alter its orientation to "track" its targets. Therefore the stabilization system must also respond to external commands. This is the first of many trade-offs that will be encountered as the stabilization system is designed.

Before we leave our overview of stabilization systems, we need to briefly discuss the methods by which the performance of a stabilization system is measured. For systems which employ optical payloads, the modulation transfer function (MTF) is commonly selected. Figure 3 illustrates degradation in MTF as a function of the sensor resolution and "jitter" of the payload during a sensor integration period. Jitter is a measure of the performance capability of the stabilization system i.e. how "steady" the orientation of the optical payload is being controlled by the stabilization system. Obviously the amount of jitter depends upon the design integrity of the stabilization system, the precision of the inertial sensor, and the environment in which the system must operate.

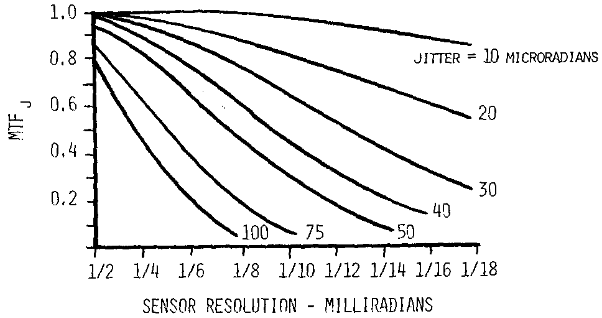

Figure 3. MTF for imperfect stabilization

The stabilization design team

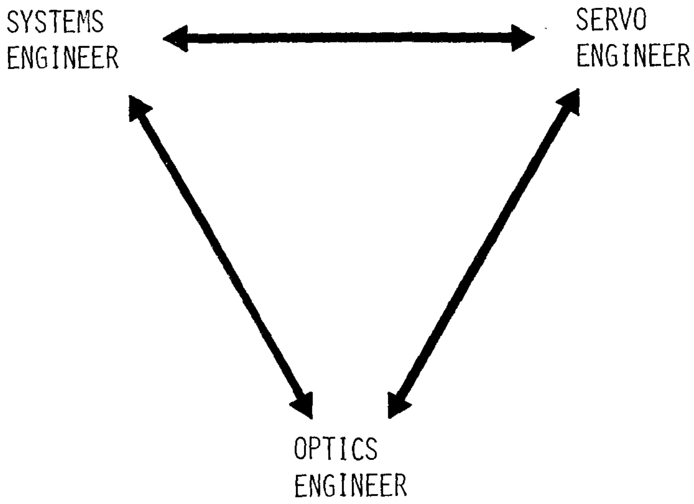

Figure 4. Stabilization design team

Design of a stabilization system to be integrated with a payload should be a multi-disciplined task. Many of the tasks discussed above involve tradeoffs, not only among various facets of a given discipline, but among and between the various disciplines. The design team may be visualized as shown in Figure 4.

The systems engineer will address the top-level specifications and their translation into subsystem requirements. He will be concerned with tradeoffs such as increased instantaneous field of view for the sensor vs. the resultant loss of resolution capability on the overall system performance.

The servo engineer will address the stabilization mechanism and its control techniques. He will be concerned with selecting the number of mechanical assemblies (the degrees of freedom), the total angular field of regard, selection of the system components, and other electrical/mechanical considerations.

The optics engineer will address the optical payload. He will be concerned with issues such as the choice for the optical scheme- reflective vs. refractive optics, optical component design and selection, vignetting, and other optical considerations.

Each of these disciplines can make choices within their own area of concern that will have both positive and negative impact upon the other areas. The best design results when each engineering discipline understands the impact of his decisions upon the other areas.

The stabilization design process

Although there are a variety of approaches that may be selected for implementation of a stabilization system, the design process is fundamentally the same for all systems. A typical "flowchart" of this process, for a prototype system, is given in Figure 5.

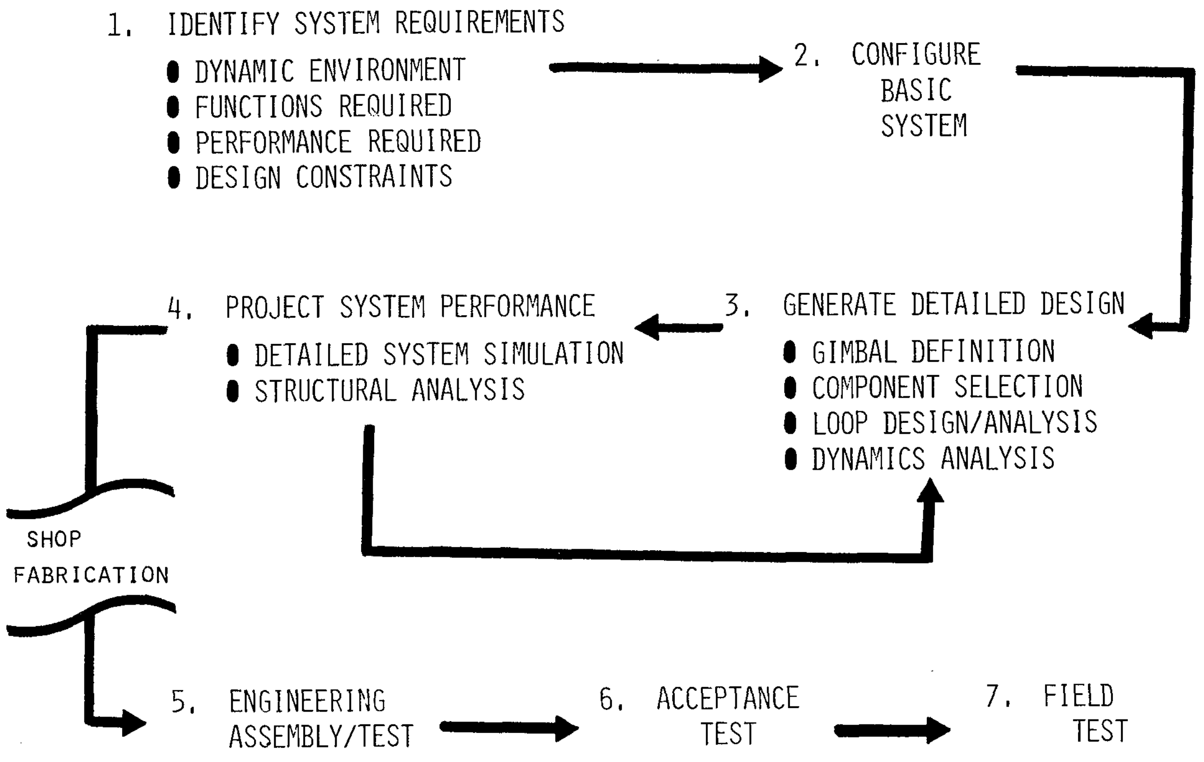

Figure 5. Stabilization design procedure

1. Identify Systems Requirements

The first objective is obviously to define the requirements for the system. This is probably the most critical step in the overall process, and perhaps the most difficult.

Top-level system performance requirements are usually generated by defining (1) the overall functions to be provided by the system, (2) the mission scenario, and (3) the type of payload to be used. The overall function of a system may be to provide,

- Surveillance
- Target Tracking
- Fire Control
- Positioning/Pointing
- Scanning
- Other

Each of these applications impose different requirements upon the stabilization system due to different application objectives, different operating environments, etc. For example, a long-range surveillance application will probably require precise pointing and ultra-fine stabilization, but may be characterized by a relatively benign operating evironment. On the other hand, a fire control applicationdue to its shorter range application- may have moderate stabilization requirements, but will almost certainly have a severe operating environment due to being used in battlefield circumstances.

The mission scenario is closely related to the function being provided and will usually be defined by the specific mission objectives. The major mission implications for the stabilization system are pointing accuracy and vehicle motion isolation. However, additional requirements that are scenario dependent might be time-of-operation, operating environment (temperature, vibration, humidity), etc.

The type payload used will dictate the degree of required stabilization precision. Optical payloads generally require more stable control than electro-magnetic sensors due to their greater resolution capabilities. Likewise, IR payloads may contain internal components, such as cryogenic coolers, which generate motions which can introduce inertial motion disturbances into the stabilization system.

Unfortunately, top level definitions of the functions, scenario, and payload are not adequate to specify the detailed performance requirements for the stabilization system. These definitions are not expressed in terms of stabilization parameters. The stabilization mechanism, as well as the optics, becomes a subsystem whose requirements must be derived from the top-level specifications. Very rarely will top-level specifications directly refer to stabilization component or mechanism tolerances; therefore the design team must make many decisions to translate overall requirements into specific parameters for the stabilization subsystem.

Nevertheless, stabilization subsystem requirements must be determined. Three general types of requirements are usually generated,

- Design Constraints: These parameters will include size, weight, power requirements, form-factor, operating environment, and cost limits. These will usually evolve as the overall system is defined from the top-level specifications.

- Dynamic Requirements: These parameters include the "motion" requirements... position, velocity, acceleration in order to satisfy the operating requirements. They may be expressed in terms that are suitable for the stabilization engineer (such as bandwidth or frequency response/step response characteristics).

- Accuracy Requirements: These parameters refer to the precision with which the mechanical motion is measured and/or controlled. Likewise the reference frame to be used will be identified e.g. relative motion with respect to other components of the system or absolute motion in inertial space.

2. Configure Basic System

After the system requirements/constraints have been defined and translated into parameters that are suitable for specification of the stabilization subsystem, then basic design decisions can be made. At this point, several candidate design concepts may be considered. The choice between mass stabilization and mirror techniques will be made; the selection of the actuation system to drive the stabilization mechanism will be made e.g. D-C torquers vs. A-C motors, gear drives vs. direct drives, etc.; the transducers will be selected e.g. type of gyro, position pick-off, pickoff sensors, etc.; and tentative decisions can be made regarding the servo loop configuration.

3. Generate Detailed Design

After the basic configuration has been defined, attention then turns to the details which will yield a complete definition suitable for release to a shop for hardware fabrication. In this step, the mechanism is defined and detailed drawings are initiated which are suitable, not only for fabrication, but for detailed structural analyses and weight-strength-production cost-and other predictions. Specific components (such as motor, pick-offs, and gyros) are selected which will meet the performance objectives and system constraints. The servo loop details will be defined, including compensation techniques which will be required to insure stability and dynamic response characteristics. Electronics are designed and interfaces to other systems are defined. Preliminary dynamic analyses are generated to indicate the level of performance that will be achieved....but these analyses are usually limited to first order effects.

4. Project System Performance

The detailed design that results from the previous step is then closely examined to verify that the desired level of performance will be achieved. This is usually accomplished by generating a detailed system simulation which accounts for the mechanism characteristics, the detailed parameters of the components, allowable imperfections in the design, effects of the environment, and other factors which will affect the overall behavior. For example, one of the key considerations will be structural analyses; design constraints will usually place limits on the overall size of the system which thereby prohibit overdesign of the mechanism, yet the dynamic requirements of the system will usually dictate that the maximum performance will be required from the system. Therefore, trade-offs are essential to minimize structural interaction, yet also meet small size and weight constraints.

The simulation and structural analyses performance prediction are used to verify that the system which is finally constructed will meet the mission objectives. However this analysis is also used as a design tool...when results are obtained which do not meet system objectives, then design changes are made to improve the performance. The feedback path in Figure 4 between steps 3 and 4 is intended to show this iterative process. After a suitable design is achieved, the design is released for fabrication of the mechanism, components are purchased, and electronic assemblies are constructed. In the meantime, the payload is also being designed and fabricated.

5. Engineering Assembly/Test

After all of the mechanism is fabricated, the components are received, and the electronics are constructed, then they are integrated into an overall working prototype. It is not unusual for a "dummy" payload (with the same formfactor and inertial characteristics as the system payload) to be assembled and used during the initial integration and test of the stabilization system. This allows the stabilization design team to conduct characterization tests and make modifications, if necessary, without tying up the design engineers who are concerned with the payload.

When subsystem tests are completed on both the stabilization and payload, then the overall system is integrated and tested.

6./7. Acceptance and Field Tests

The last steps in the design and assembly of a prototype stabilized system are acceptance test (as a stand-alone system) and field tests (when installed in the intended vehicle). At this point, the system may move into production status.

Optical design decisions

Optical design choices are among the key drivers which ultimately determine the performance of a stabilized optical system. These choices which are made to achieve the optical performance objectives also have a profound effect upon the considerations that must be made when designing the remainder of the overall system. The relationship between the optical issues and the stabilization issues is illustrated below.

OPTICAL ISSUES	OPTICAL DESIGN PARAMETERS	STABILIZATION DESIGN PARAMETERS	STABILIZATION ISSUES
Optical energy	Overall focal length	Gimbal configuration Number of gimbals	Pointing accuracy
	Effective aperature size	Mass vs. mirror Gear driven vs. mirror	
Resolution (acutance)	Reflective vs. refractive	System components	Vibration isolation
	Color correction	Motors	
	Magnification	Gyros	
MTF	f/stop	Pickoffs	Size
	Baffles/glare stops	Drivers Tachometers	
Field of view	Lens curvature		Weight
	Aspherical surfaces	Loop design Filters	
	Lens material (refractive index)	Bandwidth compensation	
	Number of lens		
	Focus mechanism		

There are several major issues which concern the optics engineer. These include,

- Optical energy
  The fundamental purpose of the optical system is to make information about the object, or scene under observation accessible to the observer...usually in the form of an image. It is therefore necessary for the optical system to collect or gather enough energy to provide this information. Thus, the optics system must be capable of producing a "bright" image.

- Resolution
  Not only must the optical system be able to collect optical energy, it must be able to use the energy and generate an image that accurately represents the object being observed. Resolution is one of the measurements that is often used to specify the ability to produce good images. The question is raised, "How near can we position two point objects before their spread functions can not be separated?"

- Modulation transfer function
  Formally, MTF is defined as the ratio of image contrast as produced by the optical system to the contrast of the object being viewed. This ratio, which is also related to resolution, also considers the variation in optics performance as a function of the spatial frequency (cycles per unit distance).

- Field of view
  Field of view is usually considered a design parameter rather than a fundamental issue of the optical system. However this characteristic is often cited as a fundamental specification for the optical system due to its critical effect upon the mission success or failure for the optics system.

In order to meet the system specifications for these issues, the optical engineer will make numerous trade-offs and finally select the design parameters for each application. For example, in order to increase the energy gathered by the optical system, the optics engineer may want to increase the effective aperature of the system. In order to meet increasing resolution requirements, the designer may want to increase the effective focal length (if he is not at a diffraction limit for the assumed aperature); likewise he may wish to increase the effective aperature.

When the optical parameters are identified, then the optics engineer must make his design choices among these parameters. There are many such parameters; a few of the obvious ones are listed in the above table. Let us now turn to the impact of the choices made for these parameters upon the LOS stabilization system. Since the stabilization system is an electro-mechanical assembly, one can generalize by stating that <u>any choice among the optical parameters that affects the mechanical characteristics of the system can potentially have an impact upon the stabilization system</u>. Maintaining mechanical balance, reducing friction, eliminating mechanical resonances, configuring compact layouts, and taking other precautions can produce systems that are more easily stabilized.

<u>Mechanical Structure/Layout</u> The physical layout and mechanical structure of the optical system is fundamental to the stabilization system. Since the optical system is the "payload", its mechanical characteristics (weight, size, balance, rigidity) become the basic constraints for the stabilization subsystem. Any choices that the optical engineer can make to produce compact packages will generally result in better stabilization potential. For example, if mass balance can be obtained with a symmetrical package so that the density of the package is uniform, then the stabilization design is further enhanced. In some applications, it is possible to "fold" the optical paths in order to mount the major components on opposite sides of the system center line.

A basic problem that always faces the optics/stabilization design team is how to mount the optical system within the stabilization assembly. In many applications, the inner-most gimbal of a mechanical stabilization system is, in effect, the optical bench for the optical system. The mounting arrangement should be rigid so that boresight of the optical payload is faithfully maintained relative to the gimbal assemblies. In addition, a rigid mechanical interface will minimize structural resonances which result in movements of the payload which are not controllable by the stabilization mechanism. Structural deformation of sensitive elements can introduce uncontrollable degradation in the system either because the distortions are not sensed by the stabilization feedback sensor (gyro) or because they are at a frequency beyond the response capability of the servo system. On the other hand, the mounting configuration must not produce deflections in the optical chain which then introduce distortion or other aberrations. We must recognize that rings, or other mounting components, for the optical elements should be viewed as a part of the mechanical structure of the overall system; not only should they achieve the optical objectives, but they must possess the mechanical integrity to serve as a part of the system structure.

A similar consideration can be made when providing adjustment capabilities for the optical system. If the optical system is intended to be adjustable, then the stabilization designer must make mechanical allowances within the system structure to permit such adjustments. This provision can hamper the mechanical integrity of the stabilization assembly. If possible, it would be better to invest the required design efforts to yield an optical system with minimum number of adjustment capabilities.

Optical systems which utilize movable mirror concepts offer unique problems and/or opportunities. Optical doubling means that the optical elements do not physically move one-for-one with the system LOS. This means that the control mechanism is not directly tied to the phenomenon being controlled. As a result, movement of the control mechanism in inertial space does not exactly correlate with movement of the LOS....this situation is not as good as the case where a direct correspondence exists (assuming all other things equal).

Another consideration with reflective systems is that the mirror size can become quite large for applications where large fields of regard are needed. Large mirrors obviously translate into larger volumes for the remainder of the system. If high optical fidelity is required over the entire field of regard, then exacting mirror specifications such as flatness and reflectivity may be induced. The system engineer should be particularly aware of opportunities where the system specification can be relaxed at the edges of the field of regard e.g. if some vignetting is permissible, then the overall size can be reduced. Flatness of the mirror generally determines its thickness and thereby its size and weight. Light weight alternatives such as honeycomb structures should be considered. Mounting of the mirror can also have an impact on the overall system. The mirror surface must be parallel to the axis of rotation through the mirror support gimbal trunnions. A useful suggestion might be to make the blank for the mirror as a part of the trunnion assembly which would then minimize the need for mounting and alignment of the mirror.

Focal Length Longer focal length generally means larger volumes for the overall sensor payload. If the volume is achieved by lengthening the payload for a given diameter, then the swing area for a given field of regard will be larger and the moments of inertia for the load will probably increase. This, in turn, dictates that larger torque motors must be used, which then leads to more weight and larger power consumption. The optics engineer should look for opportunities to trade-off focal length with aperature size in order to achieve a mechanically balanced package.

Field Of View In some applications, it is possible to increase the field of view of the optical system and thereby reduce the required gimbal coverage to accomodate a given field of regard. If required gimbal coverage is reduced, then the overall system may be reduced in size and the need for special designs to avoid vignetting will have been reduced. If the allowable envelope for the system is limited, this may be the only practical solution to accomodate a sizeable field of regard.

In some systems, a switchable field-of-view is required. If this is the case, then the mechanism should be designed so that the location of the center of gravity and change in balance of the system is minimized for the allowable positions of the mechanism. Likewise, the mechanism must be rigidly designed so that its mechanical resonances do not introduce inertial disturbances into the system.

Perhaps one of the most beneficial decisions that can be made by the systems engineer is to specify only the absolutely required field of regard. When the field of regard becomes so large that fixed, one-piece optical windows can not accomodate the large look-angles, then an additional servo system must be designed to move the entire window assembly. This is an additional subsystem that may be completely eliminated if the field of regard can be reduced.

Focus Mechanism Adjustable focus is usually achieved by physical movement of some optical component. Obviously, this movement should be done in such a manner to maintain balance and minimize introduction of mechanical disturbances.

Number Of Optical Elements Introduction of special correction elements obviously increases the size and weight of an optical system. In some applications, the reflectivity characteristics of the optical elements dictate that the viewing angle between the system and object must be held within fairly tight tolerances. In severe cases, this may require extra optical mechanisms if the angle must be maintained over a wide field of regard.

Conclusion

Our purpose has been to briefly review some of the common techniques for designing and building stabilization systems; to outline the process by which such systems are designed; and to describe the impact upon this process of various decisions made when designing the optical system which is to be controlled by the stabilization system. A simplified rule-of-thumb would be that the optical engineer should attempt to select his design parameters in such a manner so that the mechanical characteristics of the optical system do not interact with the stabilization system. From the stabilization engineer's viewpoint, the ideal payload would be rigid enough so that no adverse mechanical resonances occur, would be symmetrical so that the gimbal structure can be straightforward, would be uniformly dense and perfectly balanced so that the torque requirements to stabilize or re-orient it were minimized, would be passive in that it did not internally generate any mechanical disturbances, and would have a convenient mounting arrangement which would maintain the balance as seen by the drivers which control the orientation of the payload.