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Improve your Sensor Image with Balance

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Abstract

This paper reviews the properties which inherently limit the image quality of a gimbal mounted optical imaging system. It further describes how image quality is degraded by external influences, particularly vibration, in the supporting vehicle.

The primary emphasis is to quantify, through physical principals, and verify, through experimental demonstration, the degree of static balance required to minimize the detrimental effects of external vibration to an acceptable level. The effects of dynamic balancing will also be discussed.

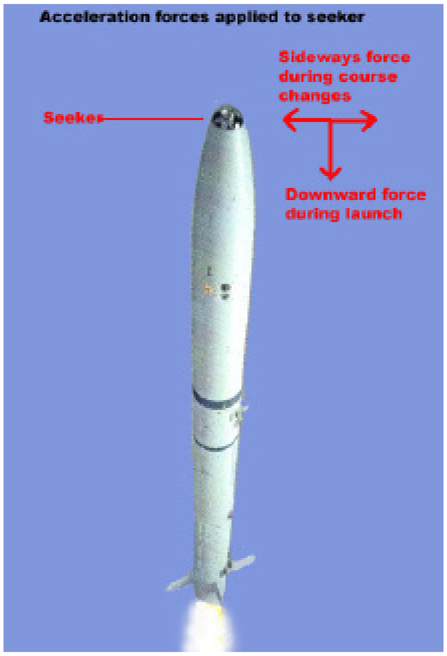
The principles developed for visible light optical systems carried by an Unmanned Air Vehicle (UAV) will be expanded, in a general way, to describe how these principles apply to infra red, ultra violet, and radar systems as well as variations to the requirements as a function of the vehicle on which they are mounted. This discussion will include manned aircraft, missiles, land vehicles and watercraft.

1.0 History

Gimbaled sensor assemblies are found in all types of airborne vehicles including missiles, manned and unmanned fixed wing craft, manned and unmanned rotary wing craft, surveillance pods, etc. Their use not only includes the traditional visible, IR, and RF sensors, but they are also used in all types of new sensor technologies such as laser designators, laser 3-D ranging and spectrum analysis, and for directing high energy weapons toward their targets. The platforms on which the sensors are mounted provide the mechanism for steering the lenses, mirrors, antennas, or other MEMS devices. A wide-ranging variety of gimbaled platforms are in use today to meet the steering needs of the sensor assemblies and their vehicles. Some examples include:

- Two-axis single plane (two co-planer pivot axes that intersect at a right angle)
- Two-axis, non-single plane (two pivot axes not on the same plane)
- Two-axis with "look down" (one pivot assembly not centered in 'null' position)
- Two-axis + sub-assembly (at least one pivot axis contains more than one mass that acts independently)
- Roll-axis or Roll/Nod gimbal (one axis is parallel to flight line)
- Multiple pivot-axis gimbal (course positioning assemblies carrying lighter and faster fine positioning assemblies)

Through the years we have worked with system integrators to address the need to balance gimbals in order to overcome the brute forces associated with launch and maneuvering accelerations experienced by gimbals during their missions (fig. 1).



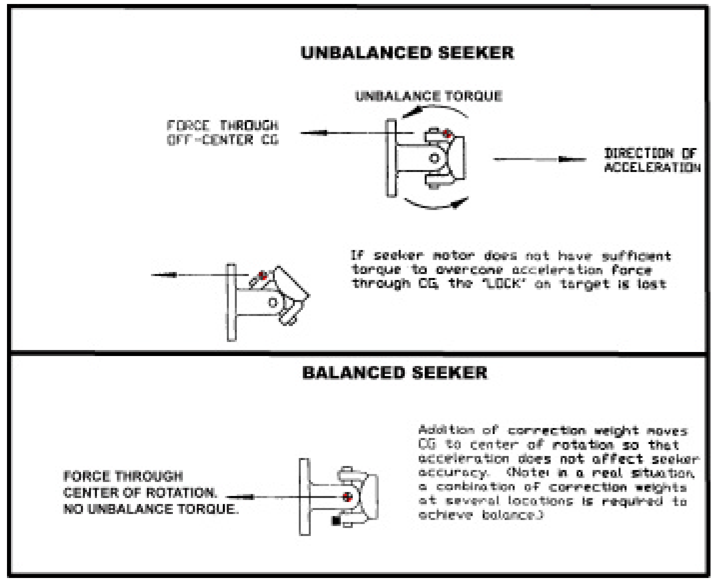


Figure 1.

At the onset, gimbal balance machines were developed to achieve the level of balance required to enable a missile to maintain lock on its target. As the performance levels increased, and the sensor platforms increased in sophistication, gimbal balance machines evolved to meet the ever increasing performance demands. As time moved on, gimbaled assemblies found their way into an increasing number of other applications. The specific needs of these new applications were similar to the requirements of early missiles but had their own nuances. Soon gimbal balance machines were found crucial in helping these other applications meet their respective goals. As before, increasing system performance demands dictated that the balance tolerance grow tighter. This trend continues today; old applications continue to "push the envelope" and require higher levels of balance, and new applications "discover" gimbal balancing as a solution to problems encountered as they "push the envelope."

Today, one of the main areas of concern for a system integrator is that of sensor performance. Various electromagnetic sensors are regularly used on gimbaled platforms. Each year the sensor manufacturers respond to customer demands and develop sensors with higher and higher resolutions. Unlike the early years where simply maintaining target lock was the primary concern, now it is mandatory that the platform stay stable enough to make full use of the increased resolution.

Anyone who has taken photographs or digital camera still shots understands that camera-shake can degrade the quality of the picture or image. The problem is made worse when low light conditions require that the shutter, whether mechanical or electrical, needs to stay open longer to allow enough light flux into the camera to record the scene. A photographer standing on a stable floor solves this problem by mounting the camera on a tripod and using a remote cable trigger to initiate the exposure. Cameras or sensor suites mounted on gimbaled assemblies are subject to many modes of acceleration. Some are intended due to maneuvering, some are periodic vibrations from engines, transmissions, etc., and some are random vibrations from the nearby structure interacting with its operational environment. No matter what the combination, the accelerations as seen by the gimbal will act upon the CG of the moving mass producing torque about the axes if the gimbal is not precisely balanced.

To better understand the effects of external accelerations on an unbalanced gimbal mounted sensor, we first look at optical resolution theory.

2.0 Optical Resolution

In a simplified optical imaging system, system resolution is largely defined by the resolution of the optics, and the resolution of the focal plane array (FPA). The basic limiting factor in resolution can be either the optics or the sensor, or both. In the following cases we will assume that a single objective lens is projecting an image directly onto the FPA. We will consider, for now, that we are working with a single wavelength of light. To start, recognize that the imaging system can be over-sampled or under-sampled. In an over-sampled configuration, the quality of the optical components limits the resolution. In an under-sampled configuration, the FPA plays the dominant role in resolution limiting. Let's first consider an over-sampled configuration where the optics, play the major role in determining resolution. Simply put, resolving power, measured in arc-seconds, of a properly shaped lens is determined by its diameter.

Taking a cue from astronomy, we will use point sources (stars) to demonstrate the phenomena. Light does not enter a lens as straight line, it enters as a wave. The wave like property causes light from different parts of the lens to alternately augment and interfere with each other. This creates a series of concentric light/dark diffraction rings at the focus. The resultant diffraction pattern is called the Airy Disk after George Airy who discovered the phenomena. The apparent diameter of the Airy Disk is directly proportional to the diameter of the objective. Larger objectives produce smaller theoretical disk sizes. Note that the wavelength of light plays a significant role in determining disk size with the longer wavelengths yielding larger disk sizes than shorter wavelengths.

When the light from two closely separated stars enters the system, the two Airy disks formed will also be close together. In a small objective system with large Airy disks, the two will appear as fussy and merged. In a large objective system the smaller, sharper disks will be presented with clear separation between them. Another astronomer, William Dawes empirically determined the ability to resolve two distinct points as roughly equal to 115.8 divided by the objective's diameter in mm. This is known as Dawes' Limit. Dawes, being a man of his times (mid-1800's), used strictly visual interpretations to determine resolving power in real-time; he did not have the benefit of CCD imaging technology and post processing methods. Later on, Lord Rayleigh further quantified the same observation with a formula that states that a resolved condition is observed when the peaks of the two Airy Disks are separated by the FWHM (full width at half maximum intensity) radius of one of the central Airy Disks.

Dawes example: resolving power for a 254mm lens (Rayleigh method yields similar results):

Resolving = 115.8/D mm

Where-

Resolving = resolving resolution in arc seconds
D = mirror diameter in mm

115.8 / 254 = .456 arc-seconds

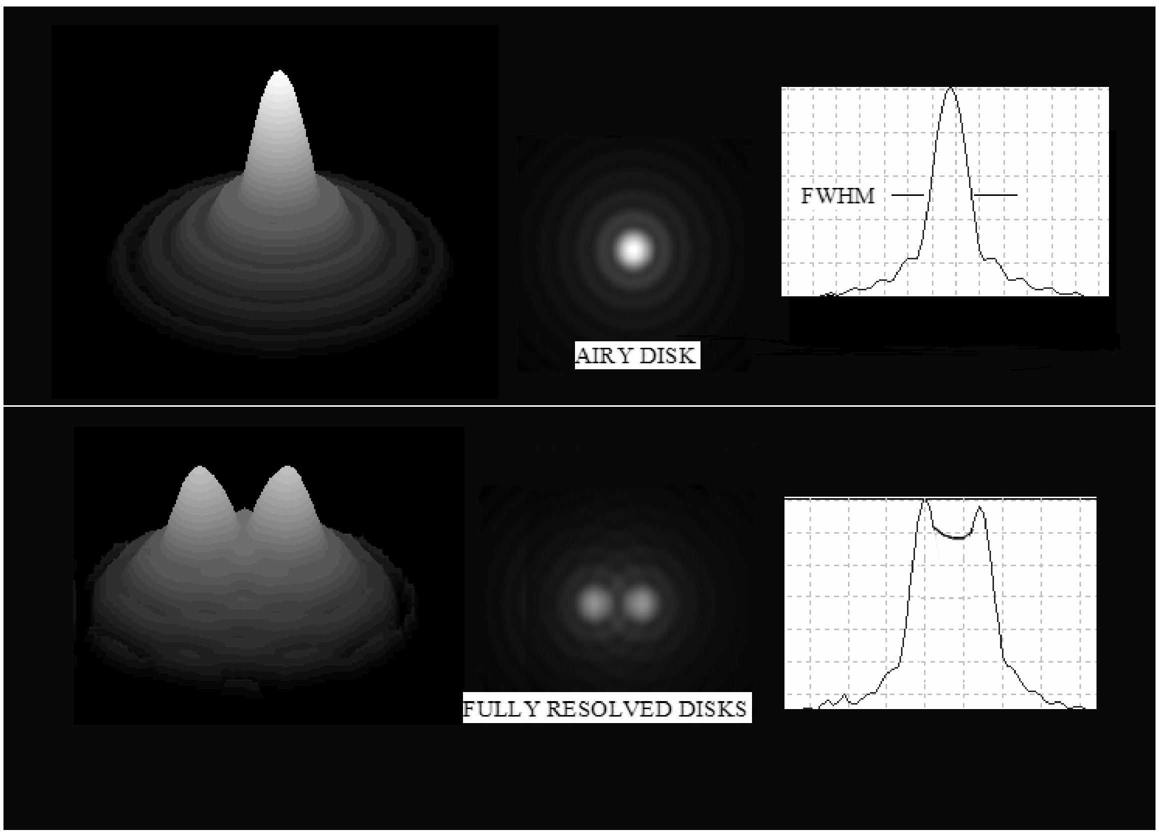


Figure 2.

With the simplified determination of theoretical optical resolution, we now turn our attention to sensor resolution and sampling. A typical CCD is a focal plane array where the active sensor surface is divided into individual sensor elements called pixels. The resolution - or number of pixels - is typically expressed in both horizontal and vertical dimensions. The physical dimensions of the individual pixels can be used along with system focal length to determine the image scale quantified in arc-seconds per pixel.

Example: a CCD has square pixels that are 5.6 microns per side and the focal length of the lens is 8108 mm.

I = (206) P/F

Where-

I is image scale in arc seconds per pixel
p is pixel size in microns
f is the effective focal length in mm

(206) 5.6 / 8108 = .142 arc-seconds per pixel

Alternatively, a second method can be used to get the same information.

An imaging system covers a known field of view measured in arc-seconds, which is determined by the distance between the objective and point of focus. This distance is the focal length of the system. If the FOV is divided by the number of pixels in a horizontal row, the horizontal resolution in arc-seconds per pixel can be calculated. Similarly, the same holds true for the vertical direction.

Since we already calculated the arc-second resolving power of the optics for specific wavelengths, and we know the arc-second resolution of the sensor coupled to the optics, we now know which of the two may be the limiting factor in determining resolution… almost!

Nyquist established a theory that addressed digital sampling of analog signals. He determined that in order to sample and represent an analog signal faithfully, the sample frequency needed to be twice that of the analog signal. Although not originally developed for electronic imaging, the Nyquist Theorem holds up generally well for our purposes. To apply Nyquist to sensor resolution, we will first recognize the optical resolution and say that the sensor must have twice the resolution of the optics in order to prevent the sensor from becoming the limiting factor, or to say: every element of optical resolution is sampled by two pixels or at twice the frequency. If the Nyquist criteria is satisfied and sensor resolution is twice that of optics, the system is said to be critically sampled. If the ratio is more than two, the system is said to be over-sampled. Less than two, it's under-sampled.

In our example we now know that our optical resolution is .456 arc-seconds and our sensor resolution related image scale is .142 arc-seconds per pixel. We now can test for Nyquist compliance.

Example:

Sample = S / O

Where-

Sample is Sampling Ratio
S is the senor image scale
O is the optical resolving power

.456 / .142 = 3.2

In this case the system is moderately over-sampled and the simple limiting factor of the system is identified as the optical resolution. In real-time observation and processing little is gained by severe over-sampling, although given heavy computerized post processing of data, resolution gains are available.

Next, we will look at an under-sampled system. Let's reduce both the diameter of the objective and the focal length of the system, but keep the CCD the same.

Consider an 80mm objective at 240 mm focal length.

Resolving = 115.8/D mm
115.8 / 80 = 1.45 arc-seconds

Image scale = (206) P/F
(206) 5.6 / 240 = 7.7 arc-seconds per pixel

Sampling Ratio = S / O
1.45 / 7.7 = 0.19 sampling ratio

In this new example, the system is under-sampled and the obvious limitation is sensor resolution. Each example, whether the system is over-sampled or under-sampled, has its place. The over-sampled configuration is characterized by generally high magnification and a narrow field of view. Under-sampled systems are typical of wide field imaging and detection applications.

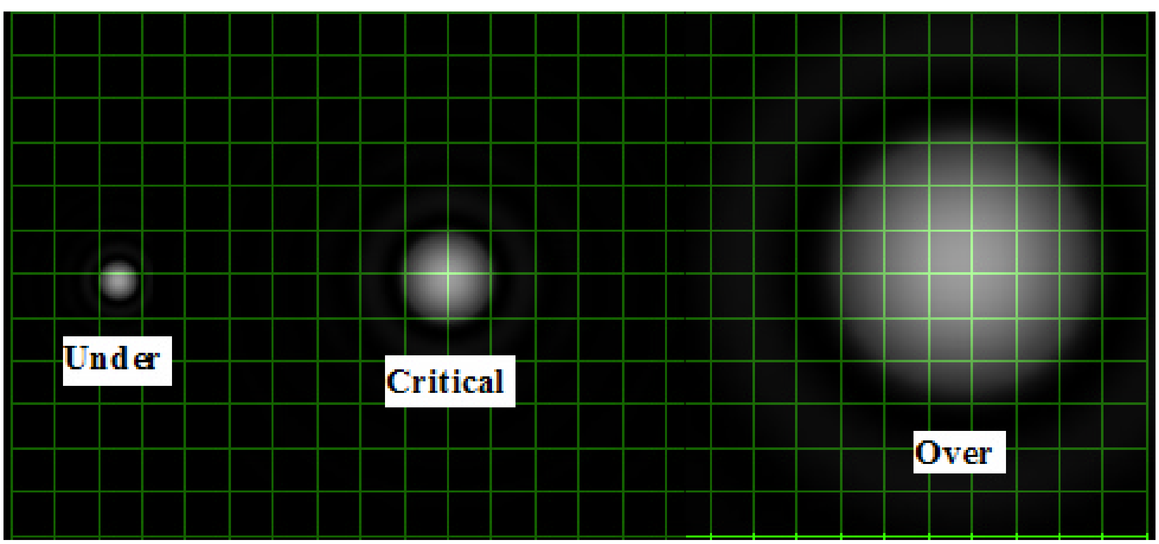


Figure 3. Pixel Grid with Various Examples of Sampling

It is now fairly simple to identify which part of the ideal system limits resolution, and how to approximate its effect. Using high spatial frequency point sources, such as stars, gives us an example which is an easy to picture, to outline the basics. In the real world things are never that simple. Most of the applications we concern ourselves with are not equated with the separation of close star pairings, but are the detection and identification of lower contrast objects of interest. We are going from the above examples based mainly on spatial separation to one more based on contrast criteria. The task often becomes one of discerning the middle and lower spatial frequencies where we are interested in recognizing patterns and shapes.

Modular Transfer Function (MTF) is an amplitude domain, scientific means used to characterize a system's ability to faithfully reproduce the scene. The function properly explores the relationship between resolution and contrast. Every electro-optical design element in a system undesirably serves to filter out the higher spatial frequencies. The low frequencies get through with high contrast, and high frequencies get attenuated with low contrast. An MTF demonstration image and sample curve is shown below. For simplicity of demonstration, we have used square wave bar patterns as opposed to the more proper sine wave patterns.

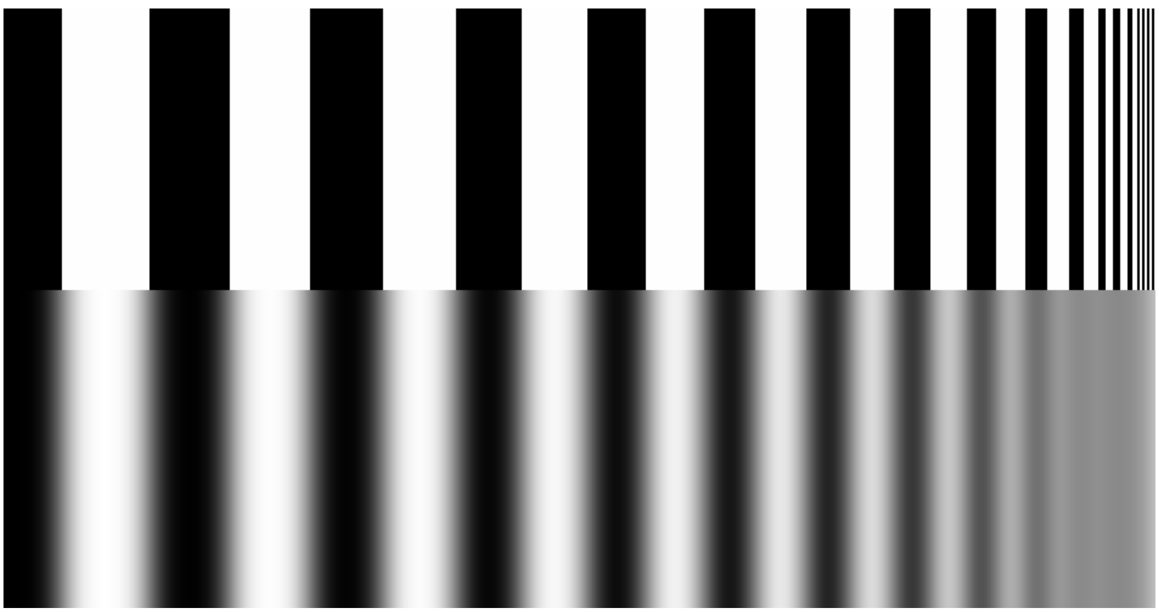


Figure 4.

The top half of the above image represents the scene being imaged, a perfect image if you will. The bottom half represents the degraded result of the imaging process as displayed to the user. Notice how all contrast is lost in the right-hand side of the lower half. Typically, this MTF loss is the result of optical resolution, imager resolution, focus, jitter, or transmission loses, or any combination of them.

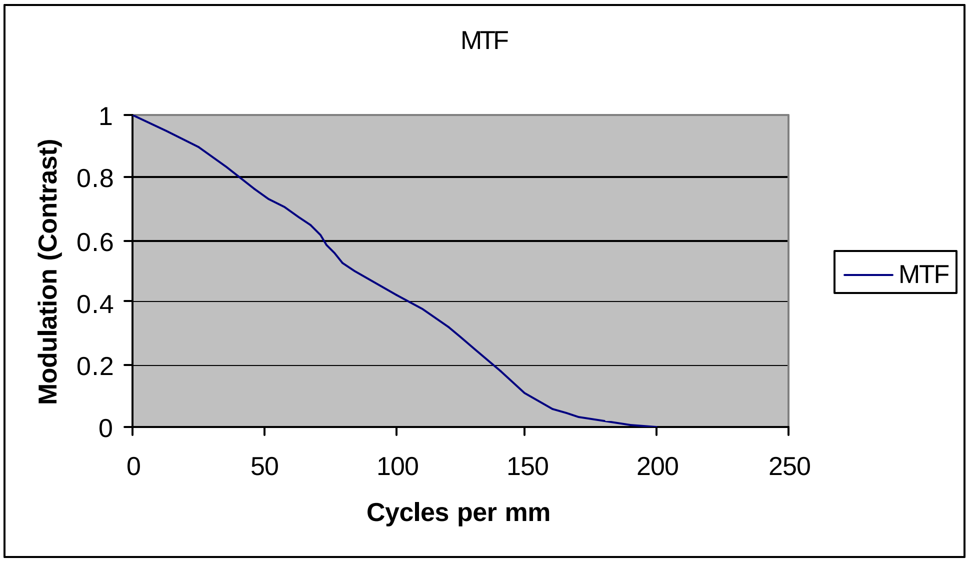


Figure 5. MTF plot of Contrast Ratio verses Frequency of line pairs at the image plane

Although the relationship between resolution and contrast is clearly shown, be aware that the systematic limits of detectability are still somewhat dependant on observer or algorithm. The cutoff frequency does not strictly limit you from resolving details beyond the limits; it simply prevents the accurate representation of them. Nonetheless, the distorted higher frequency spatial data can be useful in detection or possibly recognition. All this points out why the earlier examples given are not exactly compatible with our goals. However, the principals previously described are still the same and offer a reasonable expectation of performance in many real-time systems.

Before moving on, it is appropriate to briefly discuss a few selected issues although the topic is not limited to those presented in this paragraph. So far, our explanation has narrowly focused on a simple, theoretically perfect, single wavelength, single lens systems. Of course, this is never the case. Mirrors and lenses are subject to optical aberrations, shape-figure errors, chromic aberrations, and so forth. In practice almost all lenses are multiple element assemblies that can compensate for some of the issues but cause a loss in MTF. In some cases, as we will later find out, the losses in the lens assembly can dominate in a system where the simple lens model theoretically predicts that the sensor will be the limiting factor. Atmospheric scintillation, caused by varying density cells of air moving through the atmosphere between the sensor and the object of interest, has its own adverse effect on MTF. Optical, mechanical, electronic, and environmental factors all add up to degrade the result. While considering the mechanical, we will now turn our attention to gimbal jitter.

Jitter is multimodal, undesired, random motion with a Gaussian distribution. Of principal concern are the three axes of angular rotation. The other modes of orthogonal translation are not as much of a concern. The angular functions represent much more of a problem. This is discussed in later sections.

Jitter can cause smear in the image depending on the exposure time, sensor readout modes, the frequency of jitter and its magnitude. A reasonable approximation says that when jitter causes an image to shift less than 20%, the image will only be marginally impacted. Above 20% will degrade MTF. As with all the aforementioned factors, jitter always exists and can either be rendered negligible, or it can easily be the dominant factor in limiting resolution. How is this known? Let's go back to our second of two examples from above.

Consider the 80 mm lens and camera. We have already decided that the limiting resolution is determined by the sensor limits. In this case each pixel "sees" 7.7 arc-seconds of field. Jitter is quantified in radians so we need to bring these into the same units. Roughly, there are 4.85 micro-radians per arc-second. This means that to limit potential image smear to one pixel displacement, the system needs to be held stable to the following.

$$7.7 * 4.85 = 37.45 \text{ micro radians}$$

Using the 20% rule, the stability should be held to less than 7.5 micro radians. For over-sampled systems where the optics play the major role in determining resolution, it becomes a question of determining when Nyquist is no longer satisfied due to the decreasing MTF.

Obviously amplitude of jitter plays a role. The frequency of the jitter and the exposure time of the image also come into play. If the frequency of the jitter is very low, the magnitude very small, and the exposure time is very short, the system will freeze the motion without significant smear. Pushing the variables in the other direction always increases the likelihood that smear will corrupt the image.

To further explore this relationship please view the chart below.

Amplitude	Frequency	Exposure	Smear
none	none	fast	no
none	none	slow	no
low	slow	fast	no
low	slow	slow	some
low	fast	fast	some
low	fast	slow	yes
high	slow	fast	some
high	slow	slow	yes
high	fast	fast	yes
high	fast	slow	major

A pseudo-equation to express these relationships would look like this.

Image Stability = Force * Unbalance * Stiffness * Resolution * Time

Simply put, what matters most is; how much does the image "move" within the integration (exposure) period, and how much does it move between integration samples?

3.0 Description of Gimbal Mechanical Assembly

In an attempt to demonstrate the detrimental effects of gimbal unbalance on image quality, a simple single axis gimbal was built. (Refer to figure 6.)

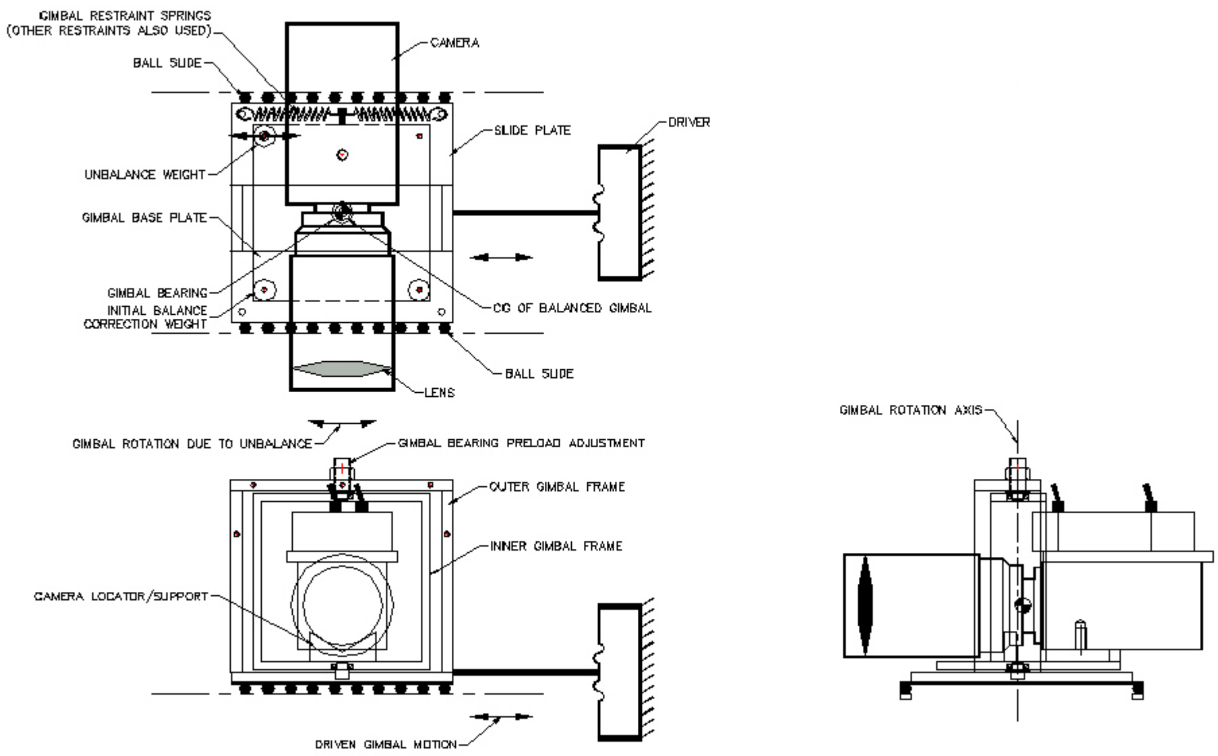


Figure 6.

The gimbal consists of an inner frame to which a camera is mounted. The gimbal has a vertical pivot axis. The camera is located so that its nominal CG is located at the pivot axis of the gimbal.

The inner gimbal frame is supported by a pair of lightly preloaded ball bearings on an outer frame. This frame in turn is fastened to a plate which rides on a pair of ball slides. Using this assembly allows us to drive the outer frame in linear translation with the gimbal inner frame free to rotate while it is being driven. Since no external rotational torque is applied to the inner gimbal frame, any rotation is due to inertial torque which can only be imposed by inertial forces acting through an unbalance on the inner gimbal frame or camera.

Springs, magnets, and servo motors were used to simulate the servo drives used in true gimbal applications to steer and hold a camera or other imaging device on a target.

Various holes were incorporated into the inner frame to permit mounting ballast weights to correct initial unbalance. Additional holes were added to permit adding known unbalance masses.

The driver is an acoustic driver similar to the drive portion of a sub-woofer. This is linked rigidly to the ball slide guided plate.

The camera is focused at about 80 feet on a target which is used to evaluate image quality in optical systems (refer to figure 7). This distance is quite small relative to the distances associated with UAV "spy" planes. The reason for this is that the lens and camera used in this exercise were not of sufficiently good quality to operate at great distances. The exercise was performed indoors to have control over the test environment which also limited the available distances.

For linear camera motion there is negligible image deterioration. This is true regardless of the direction of the motion. The reason is that for linear motion the angle subtended by the camera motion is zero and the actual distance moved is far smaller than that of the dimensions of the smallest discernable object in the image and is not amplified by the camera to target distance.

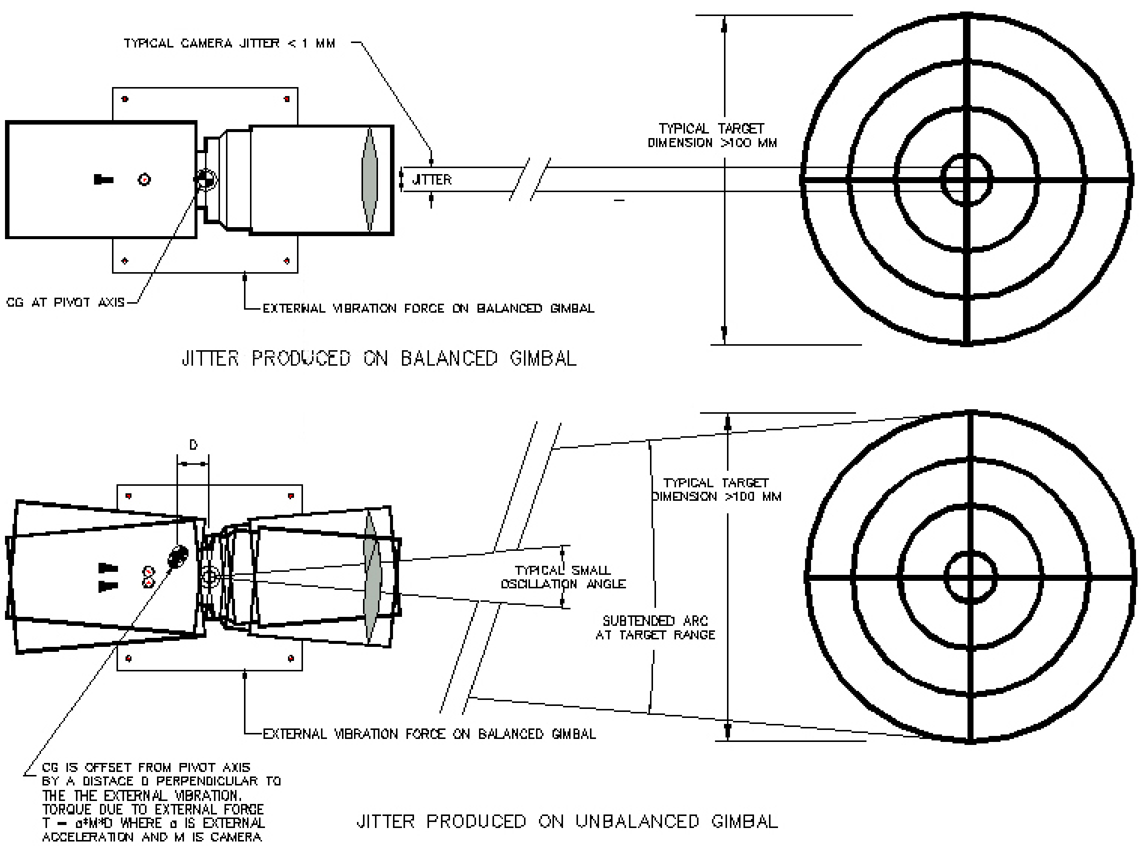


Figure 7.

It can be shown that a well balanced (but never perfectly balanced) gimbal must be driven to large amplitudes before there is any significant rotational oscillation.

However, if the CG of the gimbal is offset from the pivot axis perpendicular to the direction of motion, the camera will oscillate with very small excitation. Under these conditions, the rotational angle of the camera will very quickly sweep an angle which, at the target range, will cover a distance greater than the smallest discernible object.

By way of example, assume a perfect lens and camera which is perfectly balanced. If it is mounted in a vehicle (i.e. UAV) which imposes a 1mm amplitude vibration on the gimbal, the gimbal will move (translate) 1mm and its line of sight will move 1mm at the target distance as well. This is true *regardless of the target range*. If the target dimension is 100 mm, the effective blur will be only 1% of the target dimension.

If, however, the gimbal is unbalanced, the force on the gimbal CG due to the vibration will act offset from the pivot axis and will impose a torque. This torque will result in a small angle of oscillation at the vibration frequency. If we assume a target range of 10 Km, an oscillation angle of only 10 micro radians will result in blur over 100% of the target dimension because this small angle will sweep an arc of 100 mm at the target range of 10 Km.

The angle of oscillation is dependent on many factors including:

- Gimbal mass
- Gimbal "stiffness"
- Vibration frequency
- Gimbal natural frequency
- Vibration amplitude
- Gimbal unbalance magnitude
- Gimbal unbalance angle relative to line of sight
- Vibration direction relative to line of sight

4.0 Optical Path, Transmission and Data Paths

The Target mainly consists of an array of vertical bars having logarithmic spacing/width and sinusoidally varying density over their width with increasing special frequency (decreasing width) from left to right. The initial target was modeled from Norm Koren's website and was modified to add a second set of X2 scale bars, a vertical bar set, a license plate, and an aerial view photo of eight MiGs parked on the tarmac. The bottom bars were printed to scale valid for a working distance of 160'. To make better use of the target area we elected to decrease the working distance by half. The numbering represents line pairs per mm (lp/mm) at the focal plane. The upper scaling as seen on the images of the target is a factor of four too large, and the original lower scale is now too large by a factor of two.

A Rainbow Optics CS mount H6X8 Zoom lens is coupled to the camera. The focal length can be varied from 8mm to 48mm. Most of the tests were run at 48mm for a field of view (FOV) of 7.7 degrees. It is manually focused and has a mechanically adjustable iris. At wide open the *f* stop is 1.0 but for this exercise it was typically stopped down considerably to smaller *f* stops.

The iris was used to limit the incoming light flux in order to suppress the camera's on-board digital signal processing (DSP) sharpening algorithm which would otherwise corrupt the data.

The camera is a StellaCam EX from Adirondack Video Astronomy. Its main body is a Mintron 12V1 EX using a Sony ICX248AL ½" format CCD. The camera allows for manual control of exposure from 1/12000th second up to 2 seconds with manual control over gain. The Sony CCD is from their EX-View HAD product line and offers high quantum efficiency in a low cost, front illuminated device. The interline architecture is designed for consumer video and through on-board processing provides EIA compatible output at 30 frames per second (fps). Each frame consists of one odd field and one even field. The output is monochrome S-video.

A Sony DVMC DA2 S-Video to IEEE1394 (firewire) converter is used as a frame capture system. It captures 24-bit color, uncompressed avi streams at 30 fps although the frame rate is reduced to roughly 25 fps due to processor load. Images were captured to a HP laptop running Windows XP using either COAA's Astrovideo or Pure Motion's Capture programs.

For normal interlaced video demonstrations, Registax software was used to co-add frames to show examples of frame-to-frame motion as they appear to a real-time operator. In other cases, we wished to address the issue of smear within each frame. These examples more favorably show what a progressive scanned array sees under adverse conditions. To do this, the video clips were deinterlaced in Virtual Dub software, throwing out the Even field information while keeping only the odd field information. In this way the interlace artifacts are rightfully eliminated because they are not present in images from progressive scanned arrays. A side effect of this was that vertical resolution was cut in half but the more critical (for our tests) horizontal resolution remained unchanged. Single frames were extracted from the avi's using AVI2BMP software. Astro Art was used to obtain the pixel plot profiles. A program written by Space Electronics processed the pixel profile data and created MTF text files which were exported and charted in Excel.

5.0 Mass Properties Management Techniques

There are several ways to manage, measure, and correct the mass properties of gimbal assemblies. In general there are several mass properties of interest when working with gimbaled assemblies.

The first property to control is the static unbalance relative to the rotational axes of the gimbaled assembly. The lower the existing unbalance, the more stable the gimbal. This places less demand on any stability control system being utilized.

The second mass property to control is the Product of Inertia (POI) that exists on the moving assemblies of the gimbal. The jitter effect is more pronounced in multi-axis gimbals where 2 (or more) of the axes are mutually perpendicular. Often these axes rotate about each other at high angular travel rates though often smaller travel limits. When the inner or outer axis sweeps from one position to another, existing POIs on the inner assembly can generate torques on either the inner axis or outer axis. The generated torques must be opposed by the axes servo control system to maintain its orientation and stability. This can be true for single axes gimbals (to a lesser degree) where the vehicle or device the gimbal is mounted to experiences and high G maneuvers.

The third property is the Moment of Inertia (MOI) of each of the moving assemblies within the gimbal about its own axis. There is a trade off when managing the MOI of these assemblies. A higher MOI will create a higher stability about the axis. However, the larger the MOI the more torque is required to rotate it, yielding either a slower sweeping axis or one that consumes more power resources to attain the same sweep rates.

There are four methods of managing the mass properties of the gimbal assembly to limit the impact on the functional stability. Some of these can be used individually or together.

1. Manage a mass properties model of the gimbaled assembly during the design and manufacturing. In this technique the engineer develops a design and assigns properties with tolerances to each of the sub components to be used so that overall performance will be within acceptable limits. Then the components are manufactured to these specifications within very close tolerances.
2. Measure sub assemblies and manage (correct) their mass properties (or their placement) to bring the mass properties of the sub assembly within the bounds of the mass properties model based on a mass properties control system.
3. Measure the complete inner and outer gimbal assemblies prior to installation into the gimbal. The mass properties of these larger sub assemblies are then corrected to be within the bounds of the mass properties model.
4. Measure and correct the unbalances of the gimbal assemblies after final assembly.

Management option 1 requires very tight controls on the mass properties of the parts and is not practical as a method of control.

During the design of a gimbaled assembly, engineers will model these properties in order to calculate the systems tracking characteristics and design the stability control systems.

Often this poses a challenge for the design engineer. The predicted mass properties of these assemblies are only as good as the relationship between these models and their real assemblies. The problems with these models lie in several areas as listed below.

1. Components are often modeled as solid density objects. There are few electronic assemblies that would actually fit this model. Even a component that is a perfect square can have its CG located some distance from the center of the square due to internal mass distribution.
2. The model often uses a model mass for the component and not the actual mass from a sampling of the component. The mass of parts often vary from machining tolerances, internal sub-component mass variations, and other sources. It is,

however, ***critical*** that all components of significant mass and/or MOI have specified tolerances on these mass properties. If not, vendors exercise their freedom to alter the mass properties provided the functional requirements are not compromised.

3. If the modeling system being used allows for the entry of actually CG and mass characteristics of the components, then the issue becomes whether components being used are being manufactured to these mass property standards. If an assembly is made up of a base plate and a camera, the camera must stay within a know value for its CG location and mass or the model will be of little value in predicting the unbalances.
4. To compound these problems, component manufacturers seldom have the capability to measure any mass properties other than weight. Providing tight specifications on all mass properties only serves to limit the suppliers available and increase cost.

Management option 2 gets past some of the short comings in the first system but still falls short of the needed controls. When sub assemblies are measured, their mass properties are then known and can be managed. However, errors in final mass properties predictions and balance characteristics are still generated by cumulative uncertainty in mounting position tolerances of these assemblies. Also, the requirement to measure and maintain specific mass properties for every sub assembly is very costly.

Method 3 performs measurements of the two (or more) major gimbal assemblies just prior to mounting them on the bearing frames. Often gimbaled assemblies have very low travel angles once they are installed making CG unbalance measurements more difficult and POI measurement nearly impossible. When measuring the assemblies prior to mounting on the bearings, they can be measured on a spin balance machine for POI and static unbalance. Mass can be measured easily. The problem with this technique is that the gimbal will almost always be missing components (such as signal cables between moving assemblies) that are mounted on after bearing assembly that will affect the mass properties of the gimbal.

Method 4 gives you the best certainty that your gimbal's final mass properties are within tolerance. In this method the gimbal is fully assembled. Static unbalance about each axis of the gimbal can then be measured and corrected. With gimbals having large travel angles POI can also be measured and corrected at the same time. Since you are working with a completed assembly, when balancing is complete the residual unbalance is known to be within tolerance. The catch is that due to the manufacturing and assembly variation in sub components, using this method every gimbaled assembly needs to be balanced. After balancing, if any component of the moving assemblies is changed, the gimbal will have to be re-balanced.

There are several ways to correct for static unbalance and POI of a gimbaled assembly. Weights can be added at calculated locations, weights can be added to the gimbal at predetermined locations, or, pre-existing masses on the assembly can be moved.

It is almost never practical to add weights at calculated locations. Often the locations are blocked by a sensor or other hardware or no physical mounting point is available. These physical limitations impair an engineer's ability to place correction mass at optimal locations. This option is not very practical since every gimbal will need different weight masses at different locations.

A better solution is to define a set of locations where weights can be mounted to perform correction. These weights can be stackable structures (washers), set screws or similar masses. Then a software algorithm can be developed to take the measured unbalance (and POI) characteristics and construct a weight configuration to correct for the mass properties. If the positions and weight structures are well designed, most of the unbalances in your manufacturing population should be correctable. This technique does add mass to the gimbal assemblies in order to correct them. If total weight of the vehicle is a factor then this method may cause weight to increase beyond a tolerable level (manufacturing tolerances that are too loose can potentially require large correction masses.)

The best technique is to work with the masses that already exist on the gimbaled assembly. It may be possible to relocate some components to correct for the undesired mass properties. Moving a camera assembly that is 1/3 of the mass of the entire moving assembly mass gets you much more correction then moving or adding a correction weight that is 1/50 or 1/100 of the entire moving assembly mass. There are several practical problems with this method such as the need to very accurately change the position of the large components as well as design limits for their positions.

In most cases, a combination of the last two techniques is the best system. First measure the gimbaled assembly and reposition any large masses that can be relocated. This allows for a coarse correction of the mass properties. Then measure the new assembly configuration and use a software algorithm to construct weight structures to load on to the gimbal for small correction to the mass properties. Final fine adjustment can be obtained by moving small correction weights mounted on lead screws parallel to each axis.

It should be noted that measuring POI is always an expensive, time consuming procedure which is rarely done on gimbals. The most common method used to control POI is to design for the POI to be zero, accept whatever residual POI occurs. When performing static balance, the effect of correction masses on POI is monitored and kept to a minimum to assure that the process of correcting static unbalance does not adversely affect POI.

6.0 BALANCING THE GIMBAL

The gimbaled camera assembly was balanced on a Space Electronics GM904S2. Throughout the experiments, the camera assembly was remeasured and balanced whenever the assembly underwent a reconfiguration that affected its mass properties. At each balancing, the goal was to achieve less than 1.5 g-cm residual unbalance. As the GM904S2 is rated for 0.2 g-cm this appeared to be quite easy. When introducing a new gimbal (or a major refit of an old design) it is important to characterize the gimbal and balancing process. In this case, the repeatability of the final measurement was checked in five successive runs with no configuration changes between them. The repeatability of the process was determined to be +/- 0.5 g-cm.

Figure 8. Gimbaled Camera Assembly on balance machine

Several areas were identified that influenced the run to run variation. First, the attention to detail in cabling left much to be desired. Essentially, the extension cable that jumped the moving gap was too short to route properly, and could not loop the gap close to the pivot axis of the gimbal. The wire bundle was heavier than necessary to do the job due to the many conductors required by the unnecessary astronomy function of the camera. Second, although the main bearings used were of good commercial quality, (ABEC Grade 5), there was certainly room for improvement. Third, as with all gimbals, the travel angle is crucial to “moving” the CG far enough for the balance machine to respond. In our case, the gimbal traveled +/- 17 degrees. This resulted in a reduction in sensitivity of 2.5 times that of a gimbal measurement that travels +/- 45 degrees. Therefore, the effective instrument sensitivity was not the 0.2 g-cm as rated, but 0.5 g-cm, as we observed.

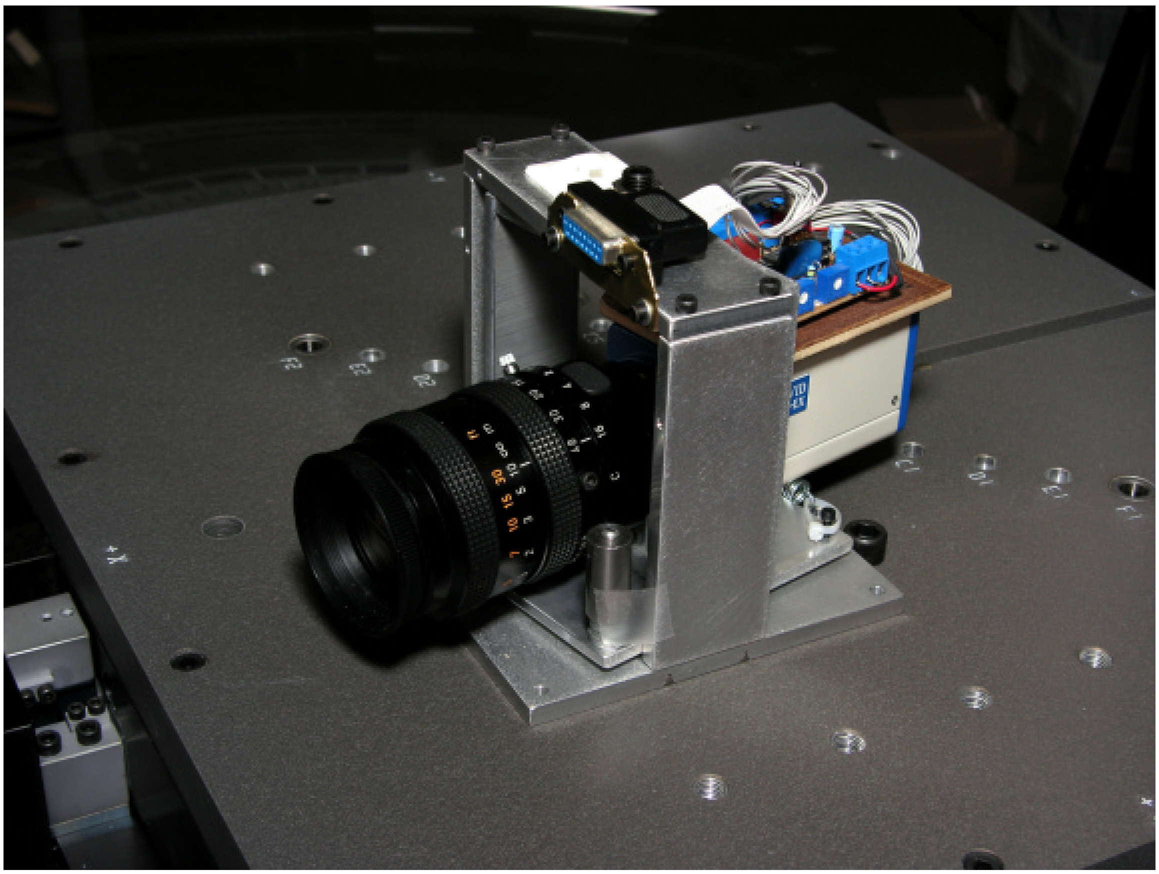


Figure 9.

Past experience has shown us that zoom lenses are problematic. Ours was no exception. Significant shifts in CG were measured when both the zoom and focus were exercised. For our balancing and subsequent vibration/MTF testing, we locked the zoom at 48mm focal length, locked the iris down, and frequently verified that the focus had not drifted during the shaking.

CG shift from zoom 8mm to 48mm = 25.7 g-cm
CG shift from focus 10 meter to infinity = 53.5 g-cm

As our testing will show, these magnitudes of CG unbalance shift that the zoom lens cause are not negligible. Assuming that focus can be locked at infinity for most applications, our 25.7 g-cm observed shift is 250 times the sensitivity of a GM904S. For applications using a long focal length with a high resolution sensor, the resultant shift in CG can tax the abilities of a highly stabilized gimbal to provide jitter-free imagery. Some applications with similar problems have designed compensating mass-motion to counteract the zoom lens CG shift. If compensating mass mechanisms are not used or are not possible, then it would be best to always balance the gimbal at your highest zoom magnification where the results of unbalance have their highest image scale effect.

7.0 MTF Test Results

Example #1: Test 27 vs. Test 28

This example demonstrates that relatively small unbalances can have an effect on MTF. Test conditions are shown in the table below.

(Note: d.a. is the displacement double amplitude)

Test Number	Peak Force	Linear Displacement	Unbalance	Excitation	field exposure	field or frames	10% MTF
	g's	inches d.a.	g-in	Hz	seconds		lp/mm
Test027	1.2	0.125	0	22.5	1/60	field	34.3
Test028	1.2	0.125	9.8	22.5	1/60	field	29.6

The following images are single frame captures out of the uncompressed avi file.

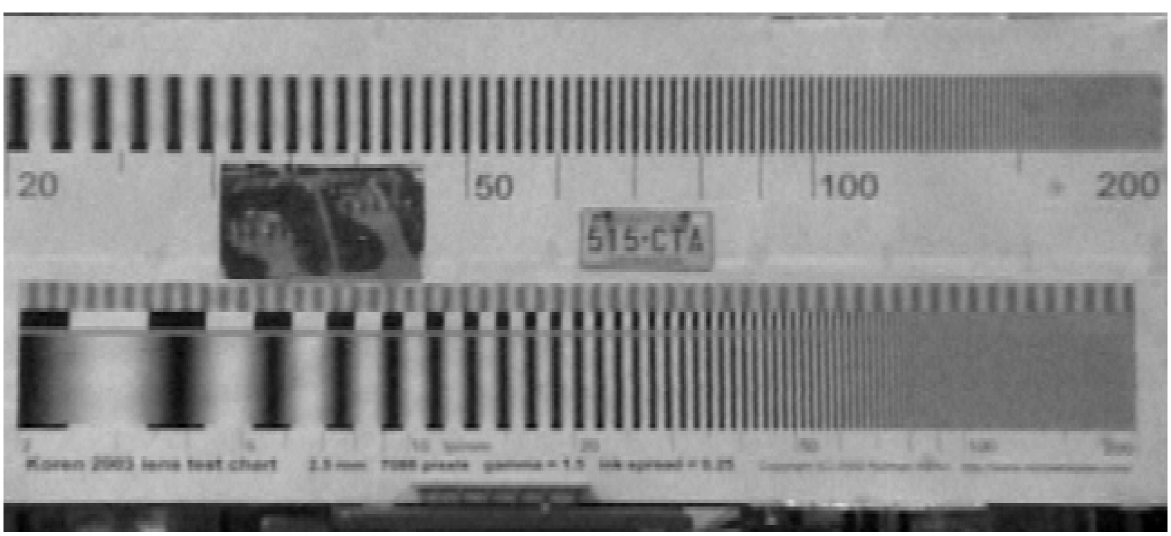


Figure 10. Test027 – contrast detail showing just past "150" on upper bar array

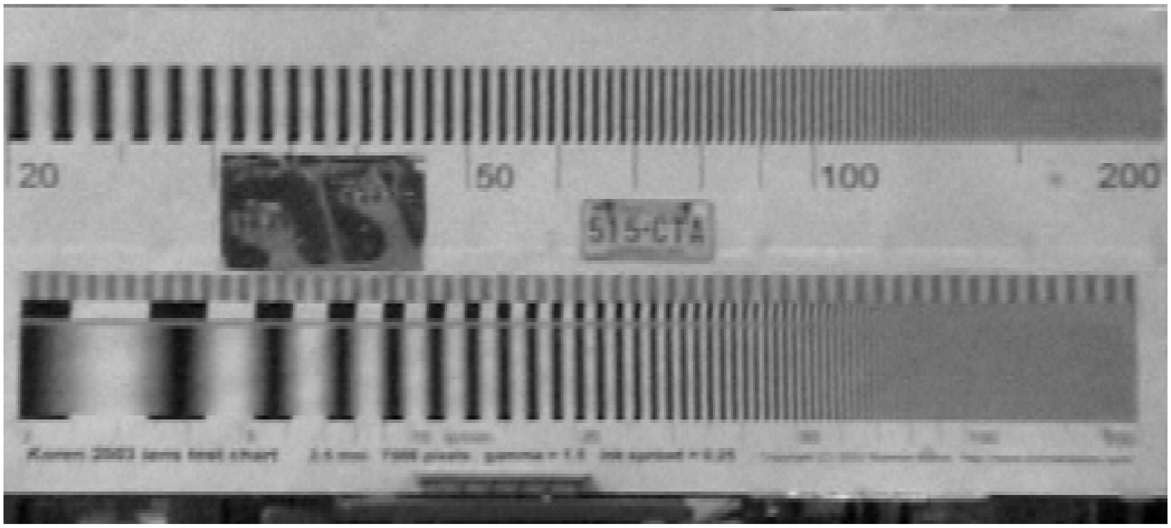


Figure 11. Test028 – contrast detail lost before reaching "150" on upper bar array.

Pixel profile charts for the two tests are shown below. The vertical scale represents pixel intensity; the horizontal scale represents CCD's horizontal pixel location. The plot samples a horizontal slice across the image and includes the entire image, even off-target image data.

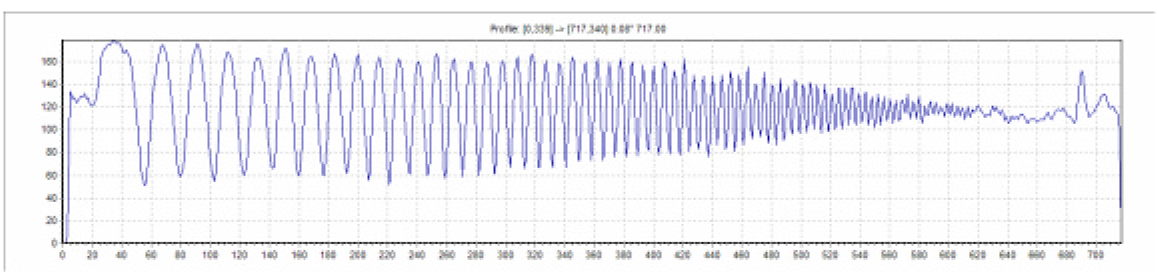


Figure 12. Test027 pixel profile across the entire image – notice data out to pixel location 610

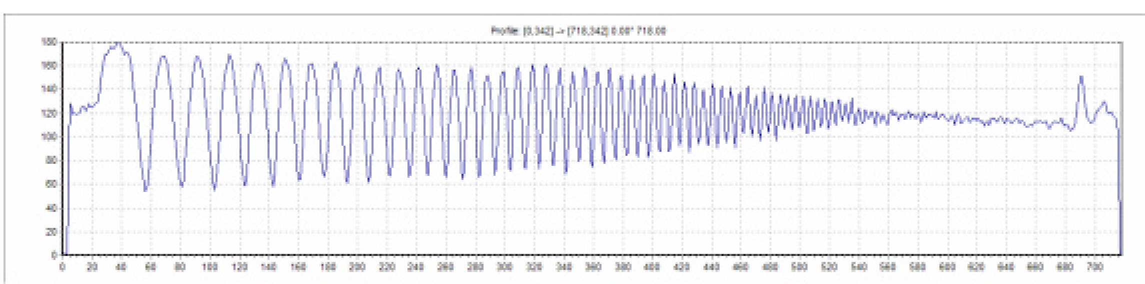


Figure 13. Test028 pixel profile – notice contrast is lost after pixel location 560 and noise dominates as we look farther right.

And finally, the MTF Graphs for each – Contrast vs. Pixel Position

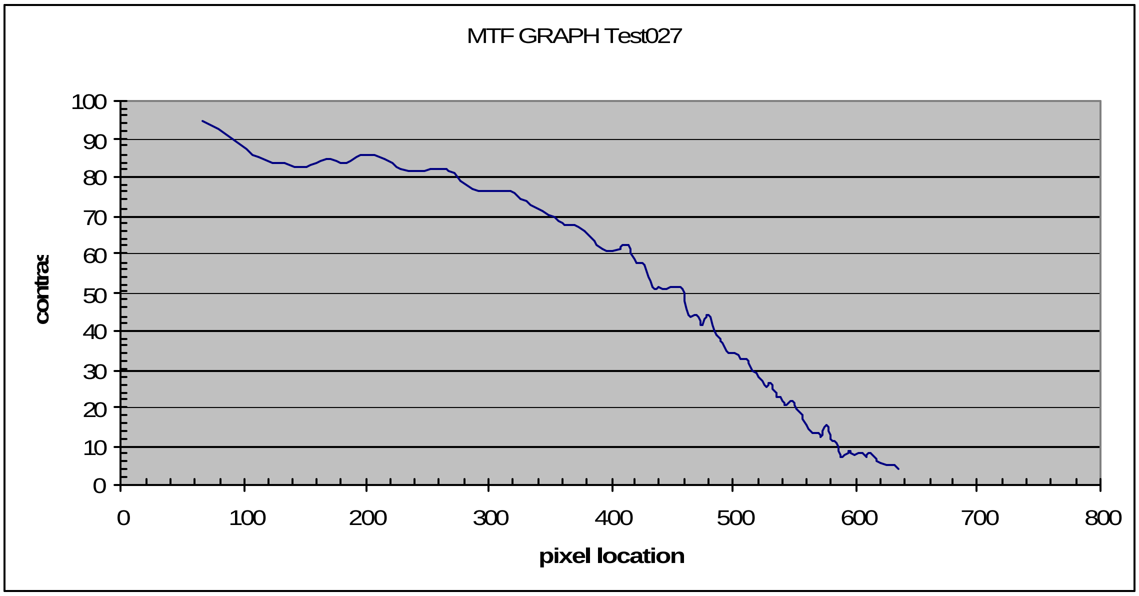


Figure 14.

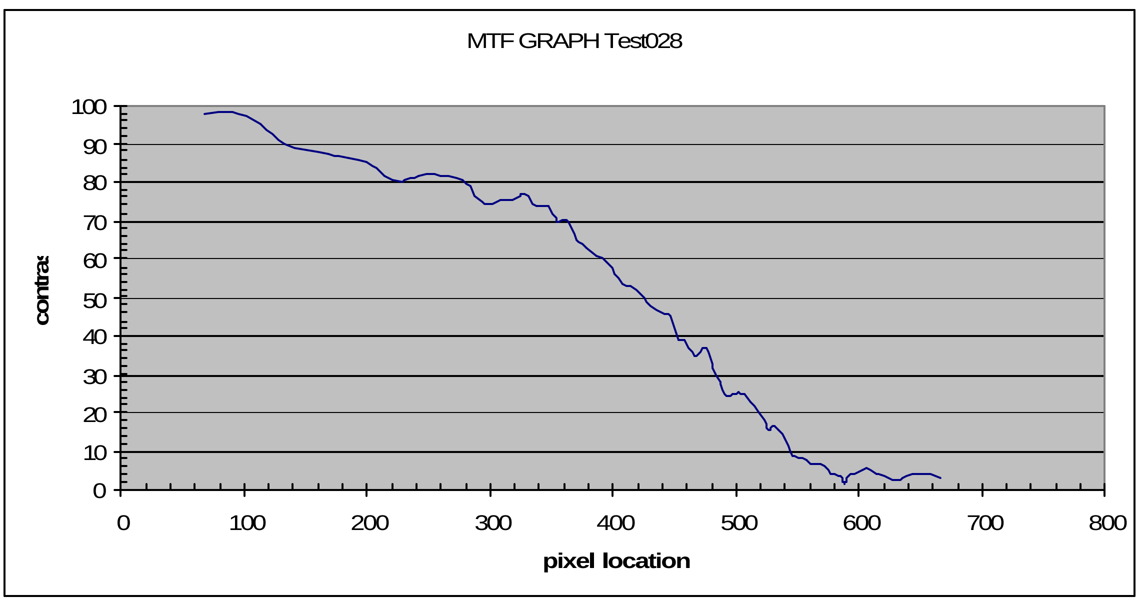


Figure 15.

The Rayleigh Criterion assumes that contrast is about 9% at the spatial frequency where contrast resolution is "lost". To make it easier to read the graphs, let's instead use 10% where one of our horizontal lines conveniently crosses. As you can see Test027 data crosses the 10% mark at pixel location 585, and for Test028 it crosses 10% at pixel location 545. To convert the 10% percent pixel location to resolution based units of line pairs per millimeter (lp/mm), we must first find and eliminate any shift of the target location as it was imaged on the frame. Because the mechanical configuration for both tests was identical; the target image was nearly in the same location on the frames for both tests. Our starting point will be a fixed offset before the first "white" peak of the upper sinusoidal bar array as read from left to right. This offset was independently determined to be 17 pixels. For Test027 the first white peak occurs at pixel 67 so the starting point is at pixel location 67-17=50, and Test028 starts at pixel 68-17=51.

Since the target is generated from a logarithmic function, we will use the following formula to convert the starting point and 10% crossing point to lp/mm MTF units.

10^ (10 percent crossing point - starting point)/640 *5

Note:
640 is the number of pixels from one edge of the MTF scale to the other.
5 is the scale correction factor.

Test027 = 10^ (585-67)/640 *5 = 34.3 lp/mm

Test028 = 10^ (545-68)/640 *5 = 29.6 lp/mm

In this first example, Test027 had 16% better spatial resolution than that of Test028 demonstrating that balancing the gimbal can aid in achieving maximum sensor platform performance.

Example #2: Test016

Control Configuration - Gimbal was in a caged configuration with 0 g-in unbalance and no linear accelerations applied.

Test Number	Peak Force g's	Linear Displacement inches d.a.	Unbalance g-in	Excitation Hz	field exposure seconds	field or frames	10% MTF lp/mm
Test016	na	na	0	na	1/60	field	35.1

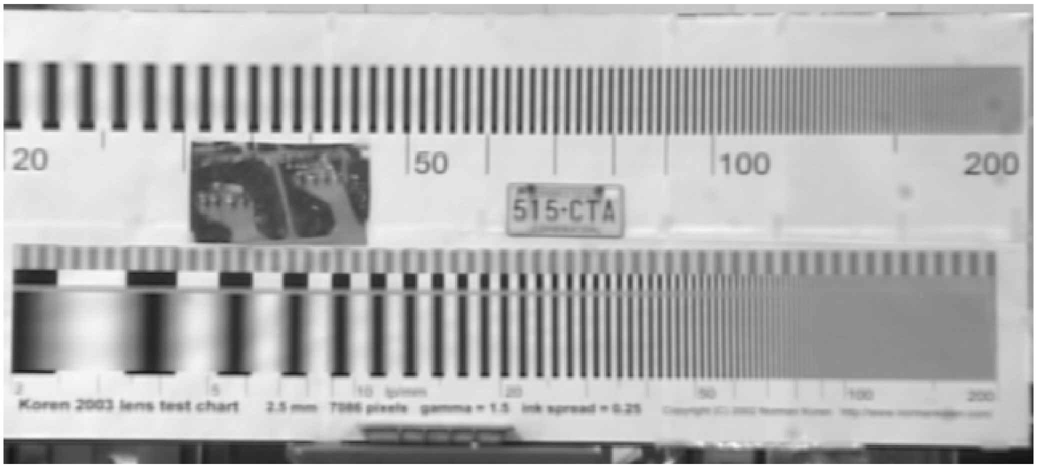


Figure 16.

Test016 represents the best that we can expect from this set up. The limitations of multi-element zoom lenses became apparent. Intuitively we expected better performance.

Example #3: Test003, Test004, Test005, & Test024, Test025, Test026

Using coiled extension springs as the restoring force, the inner frame of the gimbal exhibited a sharp Q resonance at approximately 23 Hz. At this frequency and its harmonics and subharmonics, the gimbal was very sensitive to unbalance. As could be expected, the resonant frequency changed slightly as differing unbalance masses were added changing the MOI. The results of the tests varied somewhat due to the difficulty in controlling all the variables. Matching the slip table frequency to the resonant frequency was especially critical. However, in all cases the balanced gimbal performed better than unbalanced configurations.

Test Number	Peak Force	Linear Displacement	Unbalance	Excitation	field exposure	field or frames	10% MTF
	g's	inches d.a.	g-in	Hz	seconds		lp/mm
Test003	0.06	0.0023	0	23.3	1/60	field	28.8
Test005	0.06	0.0023	5.2	23.3	1/60	field	29
Test004	0.06	0.0023	56.6	23.3	1/60	field	7.6

Test Number	Peak Force	Linear Displacement	Unbalance	Excitation	field exposure	field or frames	10% MTF
	g's	inches d.a.	g-in	Hz	seconds		lp/mm
Test025	0.06	0.0023	0	22.9	1/60	field	21.3
Test024	0.06	0.0023	9.3	22.9	1/60	field	10.1
Test026	0.06	0.0023	110	22.9	1/60	field	7.3

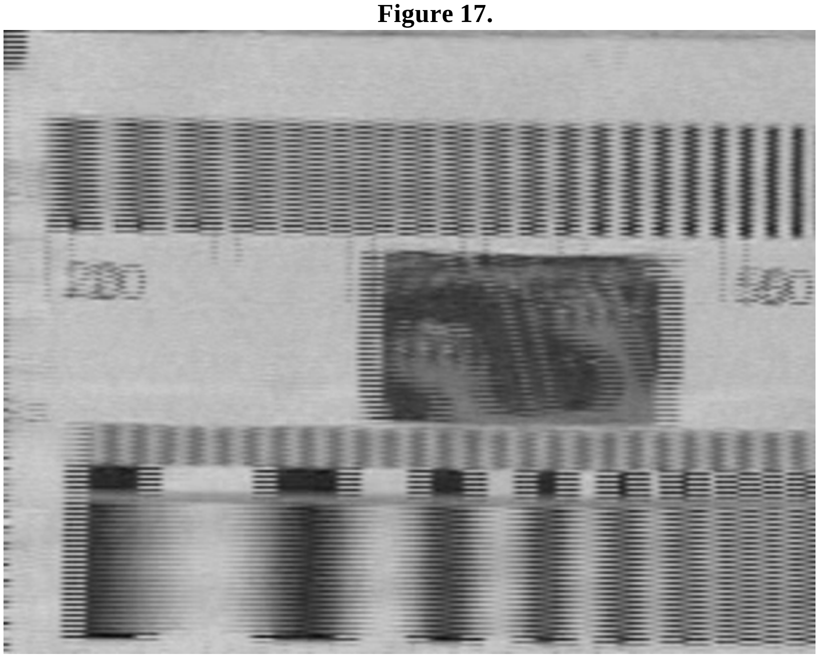
In the first grouping, adding a small unbalance had no significant effect. In the second grouping even the well-balanced gimbal experienced some degradation and adding a small unbalance, further decreased resolution by a factor of two. In both groupings the larger unbalances (56.6 and 110 g-cm) taxed the setup to its mechanical limits where the extension springs periodically went slack as the gimbal motion bloomed.

Example #4: Test012, Test013, Test014, Test015

For this grouping, the excitation frequency was set just above resonance with a large fixed unbalance mass mounted to the gimbal. Our camera has an interlaced video output, but as in all the tests demonstrated thus far, we have deinterlaced the video stream to simulate how progressive scan cameras would record in single frames.

Below is an example of a single frame capture from an interlaced video stream. In this case, the faster field shutter rate of 1/500 second does not improve the overall image because each frame is made up of two fields displaced by 1/30th second.

Figure 17.



Below, a single frame from the same avi file but as it would appear from a progressive scan camera. For the relatively low amount of jitter and our low resolution CCD, the 1/500th second exposure is sufficient to freeze the image.

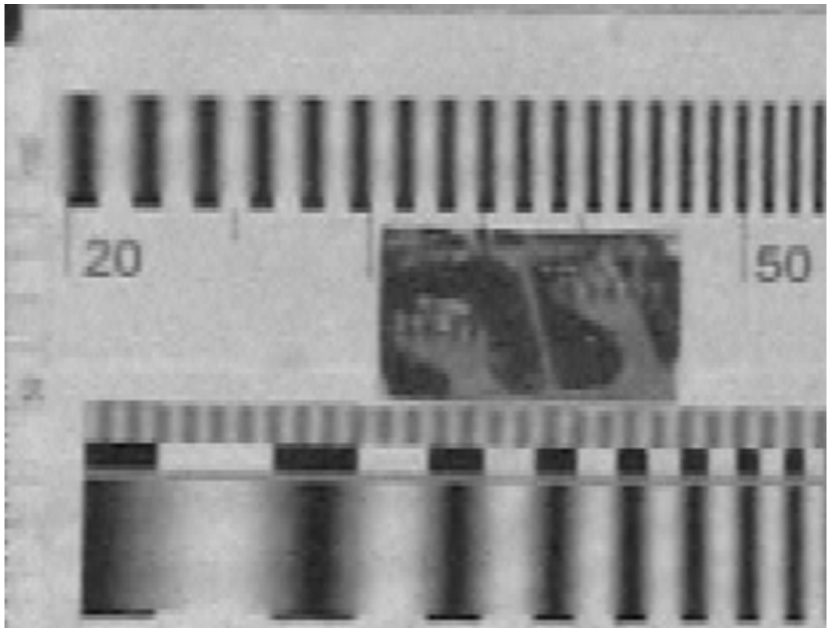


Figure 18.

Single frames are indicative of the amount of smear within each individual frame (intraframe). Electronic shutter speeds can be increased if lighting conditions permit to “freeze the motion” within each frame. Below are four “progressive scan” tests where shutter speed was increased, and the iris was gradually closed in order to keep the incoming light flux approximately the same.

Test Number	Peak Force	Linear Displacement	Unbalance	Excitation	field exposure	field or frames	10% MTF
	g's	inches d.a.	g-in	Hz	seconds		lp/mm
Test013	0.06	0.0023	110	23.3	1/60	field	12.2
Test014	0.06	0.0023	110	23.3	1/500	field	34.8
Test015	0.06	0.0023	110	23.3	1/3000	field	32.1
Test012	0.06	0.0023	110	23.3	1/12000	field	29.1

These tests show that faster frame rates can partially compensate for gimbal jitter. Test013 had the slowest shutter speed and was the only test susceptible to recording the jitter in our quasi-progressive scan mode. Increasing the shutter speed to 1/500th second and faster was sufficient to freeze the motion for our particular resonance and excitation conditions. Our tests show a slight drop off at the highest shutter speeds as our signal to noise ratio change unfavorably.

A few caveats …

First, although faster shutter rates has its place for providing improved resolution for single frames, the act of real-time observing can be very different. To an observer watching the feed, even the progressively scanned arrays will show that the video jitters from frame to frame.

When considering interlaced video, the problem will be exacerbated by interlacing artifacts introduced into each frame.

Second, not only are favorable lighting conditions required to effectively compensate for motion, but the camera has to be capable of achieving faster shutter speeds and higher frame rates.

Third, the resonance and sinusoidal excitation we applied are quite low in both frequency and amplitude. Keep in mind that our test setup used a single axis gimbal with a single mode of sinusoidal excitation. Gimbals with complex response to wide spectrum multi-mode random vibration may not have cameras which can expose fast enough to freeze the motion.

Once again, balancing offers a universal solution that covers all situations encountered.

Example #5: Mpeg5, Mpeg5d, Mpeg4

Representation of live video feed

Because this paper cannot show live video, we have taken the liberty of averaging a stack of 30 frames for each of three avis. Please note that to simulate the video feed, these images were not registered to correct for image shift. By overlaying successive frames we have simulated what your eye would see in one second of video at 30 fps. The three images below are X2 blow-ups of the license plate section of the target. Each had identical unsharp mask processing to enhance features for printing purposes.

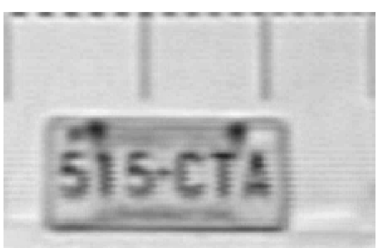


Image A

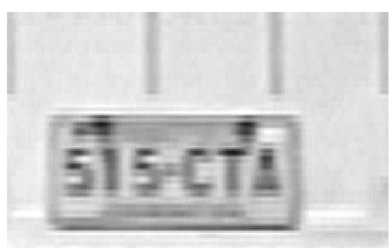


Image B

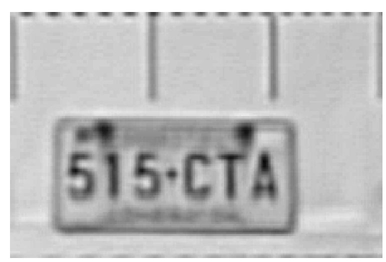


Image C

Image A is from interlaced video taken by a gimbal mounted camera which has a 9.8 g-in unbalance, excited near resonance at 22.7 Hz with .015g peak force. Image B is from the same original video as Image A except the video was deinterlaced to simulate a progressive scan FPA. Image C is from a video feed from a caged gimbal. Notice that there is little difference in clarity between the first two images, even where the 1/12000th second fields effectively froze each image. Successive frames spaced 1/30th second apart leave the impression of a blurred video even though the progressive scan version has sharp sub-frames. Image C demonstrates that only an extremely stable gimbal will allow for clear real-time video.

8.0 Servo Stability and Balance

The traditional call for balancing a gimbal stemmed from ensuring that the torque motors responsible for positioning and target lock had enough torque to deal with overturning moments caused by acceleration. The motors had to be sized properly in order to prevent the seeker from losing target and not recovering. So let's say that the motors are adequate to deal with the residual unbalance and accelerations expected. What is the next concern? The concern directly addresses the servo control loop's ability to hold good stability against any torques generated by CG offset from the pivot axis, and the accelerations that act upon it. Good stability is whatever is needed to achieve the image clarity desired *(or any other resolving power metric for other sensor technologies).*

In our related experiment, a closed loop servo replaced the permanent magnet and extension springs to provide the restoring force. The entire electro-mechanical arrangement was cobbled from parts readily available in our shop. The electromotive driver was a magnet and a coil disassembled from a relay, the angular feedback was a potentiometer, and the electronics was a pulse width controller from an RC servo. Not even close to the best, but it was adequate for our purposes. From a performance standpoint the servo was not very linear except for a very narrow angular band of say one degree. Hence, we limited our testing to forces and unbalances that generated less than one degree of motion. The system was underpowered and struggled to hold position against the jitter induced torques. Another problem encountered was related to cabling dress adding unpredictable "spring rate" into the system. When commanded, the servo positioned and held the gimbal quickly. There was some ringing that we could not reduce or eliminate because the microprocessor based command software did not have any tuning capability. The lack of electrical schematic made analog solutions impractical.

After some initial tests, it was determined that the servo would not respond fast enough to jitter-induced torques any higher than 4 Hz. Our Slip Table was set to 4 Hz which is well within the range where the response of the Slip Table has already dramatically dropped off. Nonetheless, we were able to generate displacements of 0.085" d.a. which resulted in a rather small 0.07 g peak.

An oscilloscope was connected to monitor the correction signal sent to the driver. The gimbal was first run in a balanced condition and then run with a 110 g-cm unbalance. The results are shown in the two capture images from a storage oscilloscope shown below.

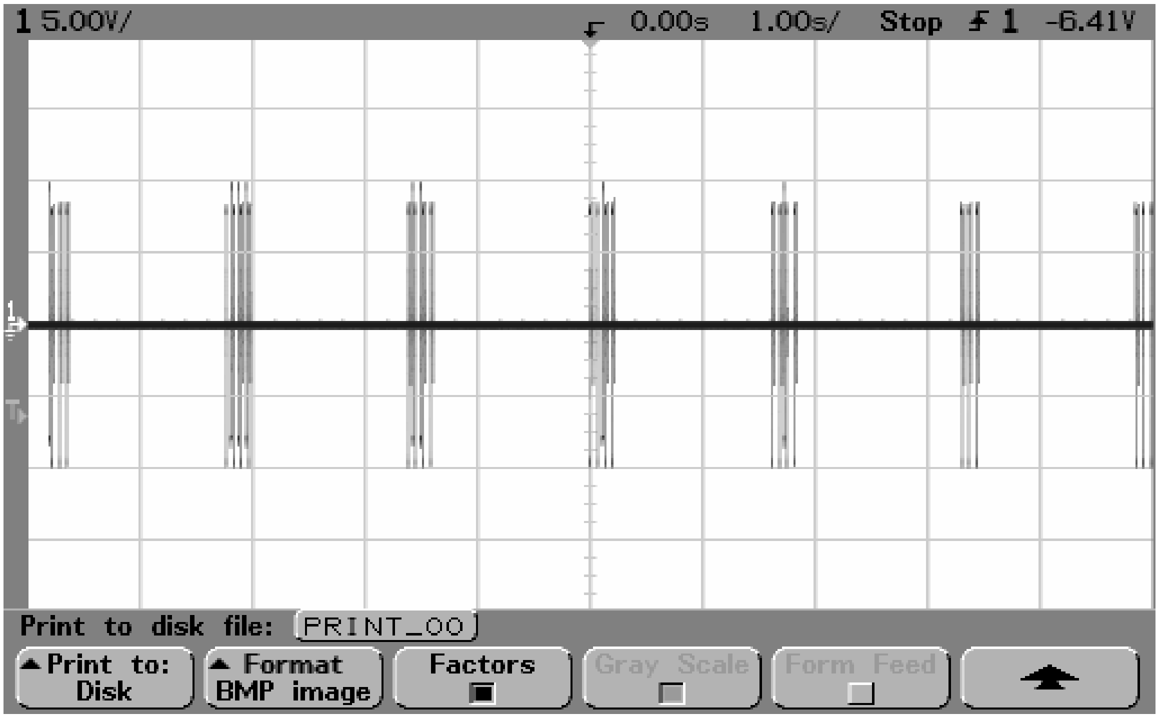


Figure 19. Correction Signal sent to Servo Driver under balanced conditions

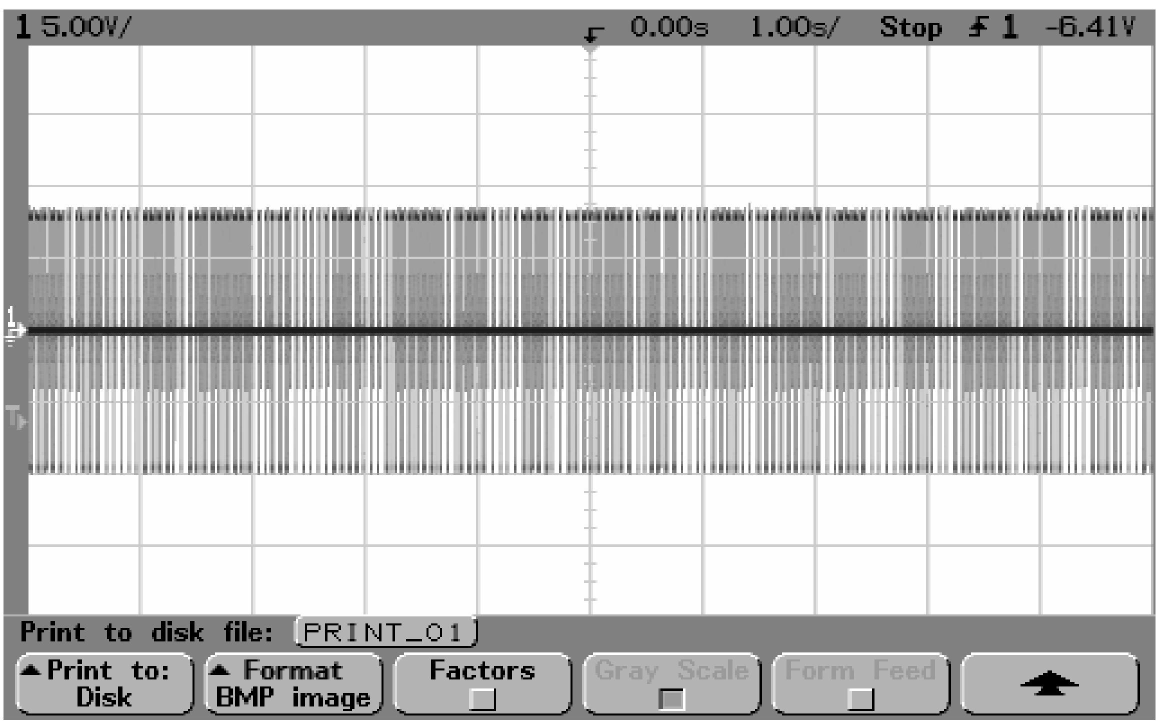


Figure 20. Correction Signal sent to Servo Driver with unbalanced gimbal

The results clearly demonstrate that the servo was required to work harder with the unbalanced gimbal. In fact, the balanced condition signal plot might not have had any corrective signal, but for the servo sometimes showing similar activity even while the slip table was stationary. Our lack of closed loop tuning resulted in periodic 'burps' where the gimbal would kick a bit, then recover.

Obviously and intuitively, if the gimbal is balanced, there is no CG offset (from the pivot) for the accelerations to work against, and the servo is not called upon to take corrective action. Gyro-stabilized sensor platforms exposed to harsh operating environments will constantly call for correction if the gimbal is unbalanced. Power expenditures will be increased over that of a balanced assembly. Furthermore, if the designers targets a low residual unbalance upfront, they can select smaller torque motors further reducing mass and the propulsion energy committed to that mass. For applications such as UAVs where SWAP (size, weight, power) are mission critical, a balanced gimbal which is lighter and balanced can be a huge advantage. Resources previously committed to the gimbal are freed up to be allocated elsewhere. Every watt/hr. saved at the payload pays loiter time dividends on electrically powered craft. Every gram saved on the payload is a gram to be spent on increased fuel load; consider that the energy density of electricity storage to combustion fuel storage is usually stated at 1:3: another win.

9.0 Bandwidth and Balance

The airwaves are running out of bandwidth. On today's battlefield, bandwidth limitations are one of the chief concerns. Telemetry from UAVs, rotary winged craft, fighters, etc, are relayed to ground commanders who require the most expedient decision chain possible. All this transmitted data has created the network centric method of data management. One of the tools used to ease the data load on these networks is that of video data compression. Real time video demands significant bandwidth by nature. Compression is integral to today's battlespace, and MPEG type algorithms are among those commonly used. Compression algorithms respond favorably to cleaner data.

MPEG compression uses a decoder and encoder set (a codec) to remove spatial, temporal psycho-visual redundancy from a video stream reducing its size. This technique reduces the data need to transmit an image to a fraction of the original size; however there are some draw backs when dealing with an image with motion. Video encoding and transmission systems use two different bit rate controls for the data streams. The two bit rate control methods are Constant Bit Rate system (CBR) and Variable bit rate (VBR).

CBR uses a constant bit rate for the stream of encoded video data. In these systems the compression ratio of the encoder is fixed. The encoder compresses the video data stream to a fixed compression ratio in order to meet the defined data streams bit rate. If a video contains more redundancy the compression takes very little time with little visual affects to the content. However if the video contains little redundancy due to intra-frame or inter-frame instability, the decoder is forced to apply more compression. In the worst case the image will become blocky and the detail will be lost.

Variable bit rate (VBR) uses a variable bit rate for the stream of data. In these systems the more redundancy in the video content the higher the compression ratio and less bandwidth taken for transmission of the data stream. VBR systems also have a configurable maximum bit rate. In a VBR system the encoder compresses the video content to (at a minimum) fit in the maximum bit rate stream. When the video has more redundancy then the encoder compresses the content more. This has the affect of increasing the compression ratio for stable images with little or no effect on the content viewed by the operator when decoded.

Older compression systems can cause blocking and loss of detail in live action motion or unstable images. MEG-4 10 (H264) is one of the latest compression systems for dealing with motion and high compression ratios. This compression system requires much more calculation to achieve the higher compression rates and retain motion detail. In a real-time system, this algorithm requires an order of magnitude increase in processor power over the needs of the older MPEG-2 techniques. Dedicated processors are often used for this task, leaving the main system control processor free for command and control functions. Minimizing the motion and instability in the video stream being processed shrinks the processor burden and, in some applications, allows the use of the older compression algorithms. This opens up more processor bandwidth for other functions.

One of the many techniques used by MPEG to accomplish compression is to compare the content differences from frame to frame, and store only the differential results. This is another area where balancing - to achieve better image stability - can help. A more stable video stream will have smaller differences between frames. MPEG can be encoded/decoded in either hardware or software. In a high performance situation, hardware encoding is often used. FPGA's and DSP's execute the algorithms used in software with potentially faster speeds and greater efficiency. The hardware implementation can reduce video latency as viewed by the operator, improving the decision-making process and decreasing reaction time.

Not having access to hardware encoders, we tested software encoding only. Included in our testing were MPEG2 and the emerging MPEG4 part 10, more commonly known as H.264. Both methods were tested using variable bit rate (VBR) encoding. Our assumption is that both the software implementation and the hardware implementation of MPEG H264 yield similar results, because they are both based on similar architecture as outlined in the standard.

The tests consisted of three basic configurations: a caged gimbal for the ultimate in stability, a small unbalance (9.8 g-cm), and a larger unbalance (110 g-cm). The data for the caged gimbal video image is tabulated as 'stable'. For our purposes, let's define intraframe smear as blur occurring within the CCD's integration period thus smearing within the individual frames (although they will still jitter between frames). Let's also define interframe jitter as frame to frame jitter which occurs even with faster shutter speeds that freeze a sharp image on the individual frames. Consequently, in our tests, shutter speeds were varied to evaluate the effects of smear and jitter separately. Interlaced vs. deinterlaced (to simulate progressive scan) was also included.

The results are shown in the following table.

Group 1	shutter	scanning	Unbalance	uncompressed	MPEG2	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg004	1/12000	interlaced	stable	5464.6	143.4	0.0
mpeg005	1/12000	interlaced	9.8	5464.6	157.4	-9.8
mpeg008	1/12000	interlaced	110	5465.6	161.7	-12.8
					used one-pass, medium compression	

Group 2	shutter	scanning	Unbalance	uncompressed	MPEG4 H264	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg004	1/12000	interlaced	stable	5464.6	127.5	0.0
mpeg005	1/12000	interlaced	9.8	5464.6	133.9	-5.0
mpeg008	1/12000	interlaced	110	5465.6	138.1	-8.3
					used one-pass, high quality (low compression)	

Group 3	shutter	scanning	Unbalance	uncompressed	MPEG4 H264	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg004d	1/12000	deinter	stable	1013	2.35	0.0
mpeg005d	1/12000	deinter	9.8	1013	3.29	-40.0
mpeg008d	1/12000	deinter	110	1013	3.79	-61.3
					used one-pass, medium quality (higher compression)	

Group 4	shutter	scanning	Unbalance	uncompressed	MPEG4 H264	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg004	1/12000	interlaced	stable	1013	1.43	0.0
mpeg005	1/12000	interlaced	9.8	1013	7.85	-449.0
mpeg008	1/12000	interlaced	110	1013	11.18	-681.8
					used one-pass, medium quality (higher compression)	

Group 5	shutter	scanning	Unbalance	uncompressed	MPEG4 H264	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg004	1/12000	interlaced	stable	1013	1.43	0.0
mpeg005	1/12000	interlaced	9.8	1013	7.89	-451.7
mpeg008	1/12000	interlaced	110	1013	11.69	-717.5
					used multi-pass, medium quality (higher compression)	

Group 6	shutter	scanning	Unbalance	uncompressed	MPEG4 H264	Degradation
File	seconds		g-cm	avi Mbytes	avi Mbytes	percent
mpeg003d	1/60th	deinter	stable	1013	2.52	0.0
mpeg002d	1/60th	deinter	9.8	1013	4.59	-82.1
mpeg009d	1/60th	deinter	110	1013	4.45	-76.6
					used one-pass, medium quality (higher compression)	

The amount of compression is highly dependant on the nature of the imagery. Both the amount of intended relative motion as the target is tracked or the scenery is moving, and the amount of jitter experienced as defined by the forces, frame rates, etc, play a role in determining the compression ratio. The myriads of software setting were not systematically explored and undoubtedly had a greater affect on the compression ratio than the imagery. Because of this, it is difficult to quantify the results. In an attempt to quantify the results, the percent degradation is defined as:

100 times the difference between the compressed video file size for the caged gimbal (VFcg) and unbalanced gimbal (VFug) divided by the video file size of the caged gimbal.

$$\% \text{ degradation} = 100 \times \frac{(\text{VFcg - VFug})}{\text{VFcg}}$$

Our results showed up to 700% degradation in compression ratio performance with a jittery gimbal. As such, here are our general conclusions.

- In all cases; the stable video from the caged gimbal provided better compression and correspondingly smaller file sizes than the unstable imagery acquired with the unbalanced/uncaged gimbal.

- From an encoding standpoint (Group 1 vs. Groups 2-6), both MPEG2 and H264 acted the same with the largest variation between the two being related mostly to the “quality” settings selected.

- The higher the compression ratio (Group 4 vs. Group 2), the better the caged, stable gimbal performed compared to the unbalanced/uncaged gimbal. When using higher compression ratios, H264 not only yielded the expected smaller files sizes, but demonstrated substantial improvements with the stable imagery from the caged gimbal.

- Gimbal stability seems to benefit interlaced video more than our quasi-progressive scan (Group 4 vs. Group 3). Interlaced stream compression ratios degraded significantly as soon as the imagery went unstable; likely due to the H264 having to deal with the moving, high-spatial, interlacing artifacts of the video.

- When slower shutter speeds are used in low-light conditions (Group 6), it demonstrates that a stable video stream compresses more readily. Of note here; the intraframe smear at 110 g-cm actually yielded a smaller file size than that at 9.8 g-cm. This is due to the larger unbalance having more intraframe smear. The smear within each frame means that the encoder does not have to deal with the higher frequency content and saves even more data rate. However this smaller, but blurry and jumpy video is less usable to the operator.

- Balancing may be the one avenue for image improvement for legacy hardware encoders where upgrade of that hardware may not be a viable option.

Line of sight (LOS) laser communications are under development and testing. Essentially, lasers and receivers are mounted on the aircraft and located on the ground. The lasers are modulated with data, and the two point at each other's receivers, creating a two-way link. The method is difficult to intercept, has very high data rate alleviating bandwidth concerns, and uses high precision gimbal mounted devices. The required pointing accuracy of the airborne device is dependent on the range and altitude of the aircraft but can be on the order of six micro-radians. Swarms of UAVs will be able to communicate with their ground stations and with each other using this method. Certainly RF bandwidth will be opened up by use of these high precision, highly stabilized gimbal mounted lasers.

10.0 Methods of Stability

The following points list the anatomy of a highly stable gimbal.

- Three, four, or five axes of motion provide the ultimate in line of sight (LOS) stability. Each axis stepping inward provides ever increasing isolation from the external environment and achieves successively higher levels of sensor stability. Each successive axis is required to have less angular motion than the previous. Each axis carries less overall mass, less MOI, and slews more quickly than the previous.

- Axis steering is achieved with frictionless pancake torque motors driven by a four quadrant Pulse Width Modulated (PWM) torque controller. High resolution, light weight slab resolvers are used for angular feedback to close the position track-loop.

- Inner axes are driven by limited angle torque motors (LAT) to quickly track sudden small target motions while the outer axes handle gross pointing. This is similar to your head and eyeball. The head provides multi-axis gross motion; the eyeball provides multi-axis fine motion.

- Axes are pivoted on close tolerance, precision bearings which not only carry the static radial load of the gimbal mass, but also see the dynamic radial and axial thrust g loading generated from periodic and Gaussian external vibrations. The ideal bearings are nearly friction free. They are required to work through wide operational temperature swings and must store well during long term storage.

- Extremely low-noise state of the art rate gyros sense acceleration in inertial space. These can be fiber optic gyro (FOG) ring laser gyro (RLG), or various types of MEMS coriolis devices. Usually the angular rate sensors are mounted directly to the moving axes directly affecting the imaging sensors. The gyro outputs are filtered to reduce stability-compromising noise. The error source signals are amplified and fed to sophisticated processors that estimate motion, then send feed forward inertial rate compensation correction signals to the LAT controller. The opposing torque generated counters the instability torques.

- Each axis is precisely balanced to reduce residual unbalance to a minimum. Overall correction weight mass is kept to a minimum through use of weight correction software and proper planning for balance weight locations. Total gimbal mass is lower. POI effects are tracked and kept minimal in order to prevent cross axis response. MOI of the axes is kept to a minimum to improve the response rate of the track loop and inertial control loop.

- The gimbal structure is lightweight and stiff with high natural frequency adding predictability of response to the gimbal's own control loops, as well as its relationship with the proportional navigation control (missile applications).

- An option in some applications is to affix the entire sensor platform to isolation mounts to minimize operation environment vibration transfer to the gimbal structure (rotary and fixed winged platforms).

The implementation of a stabilized gimbal, one that meets the above criteria, is very costly. According to the DOD UAS Roadmap 2005, the cost of the Predator UAV EO/IR sensor is almost a much as the rest of the craft. The Global Hawk's package ranges from 33% to 54% of the total costs. Naturally, the cost of the stabilization system is just a part of that but it should not be underestimated. There are many configurations and methods to achieve similar goals. Some are just as costly and others are less expensive with correspondingly lower performance expectations. Even with the most expensive implementations, stabilizing techniques are imperfect. For example, the noise level of rate gyros is one of the fundamental limitations on stability performance. The cost of going to a rate gyro that has $1/10^{th}$ the noise floor of what you started with is disproportionately high.

Of course, there are many longstanding variations of gimbal assemblies much different from our above example. Each has its own concerns.

- Conventionally packaged motors, lever driven assemblies, gear drives, have been in use for years. These methods, by nature, include backlash in gearing and linkages. Even if antibacklash components are used, fit, tolerances, and deflections in each part of the assembly will degrade stiffness and limit the effectiveness of stability systems. Motor cogging and nonlinearity similarly affect the system. Whether Pancake LATs are used or other means, the track loop performance is encumbered by mechanical stick/slip and is asked to quickly slew the axis into position, both of which necessitate high feedback gain and correspondingly, produce high drive stiffness. Because the error rate gain is high, the system is susceptible to noise that is amplified by that same high gain.

- Encoders, potentiometers, and RVDTs are widely used in place of resolvers. Along with resolvers, each has it own resolution, repeatability, noise, and signal bandwidth concerns. Of these, noise is considered to be one to the chief error sources. Analog or digital processing to compensate for performance limitations have their own trade offs. Even with high bandwidth designs, latency issues will eventually limit the response rate and thus cause LOS instability against higher frequency vibration stimuli.

- Single and two-axis gimbals perform to meet the goals of their assigned missions. Other configurations such as roll/pitch gimbals have their own configuration advantages and cost levels.

- Miniature dynamically tuned spinning mass rate gyros are still in use and have their own issues with bearing quality and resultant noise. In some applications, large spinning mass gyros are used to directly stabilize a platform. They are heavy with decent high frequency rejection but poor low frequency rejection. Spinning mass gyro stabilized gimbals partially make up for the lack of proper balance, but introduce gimbal response latency which has to be compensated for by the operator. These types of systems are usually reserved for the entertainment industry and news media.

Other factors affect stability performance. When the pivot bearings are under heavy g loading, they may not respond in a linear fashion. Electronics cable dress and plumbing routing concerns add to the coulomb torque unpredictability. Predictive motion algorithms do not like nonlinearities and thusly provide poor corrections. Sample rates of digital filters become limiting factors as do quantization errors. Aside from the aforementioned noise floor errors, bias errors throughout the mechanical and electronics chain are imperfectly resolved.

The point of all this is to convey that jitter stability compensation is a complicated problem and is difficult to model, both on the test bench, and under actual mission conditions. Not only are the above factors pertinent, but add to this the complexity in assessing the operational environment. Wide spectrum, random vibration is a statistical problem. The profile varies with application and mission. On the testing side, it is difficult to empirically bench test full-up gimbaled assemblies because of the difficulties in creating large, six-mode random accelerations at higher frequencies.

All closed-loop feedback systems are a balance between the gain of the loop control system and the amplification of transient errors from the feedback devices. Errors in the feedback signal from predictable sources (such as cabling binding points) can be predicted and compensated for. Errors that are not predictable such as torques generated by POI unbalances on fast sweeping assemblies can cause transients that generate instability in the gimbal assemblies tracking. Algorithms controlling stabilized platforms have trouble compensating for the sudden shock associated with gun firing or weapons launch. Any unpredicted event can fall outside the stabilization loop's ability to arrive at an appropriate solution.

Ultimately, it is best to decrease the CG and POI unbalance that exists on the moving assemblies of the gimbals so that the stabilization system is not overloaded by these error sources and it operates with its optimum performance and efficiency.

LOS electromechanical jitter correction is more complex, less efficient, and more expensive to implement when residual unbalance is high. The results of EM jitter correction, whether it is well implemented, or suffering end-of-life obsolescence, will benefit from balancing by relieving the burden on the control algorithms, electronics, and mechanical elements.

Another emerging form of motion compensation is electronic stabilization - either software or hardware based. Electronic stabilization is a method where unstable imagery is two dimensionally shifted to make the platform appear as if it's not moving. The future goal is to develop real-time precision video registration (PVR). While electronic stabilization certainly has its place there are a few points to consider.

- First, it places processing demand on-board where processing resources may be already committed, or places it externally where transmission bandwidth becomes problematic. In general, it may not be possible to insert new processing modules into existing systems.
- Second, since the method demands processor time, some video latency will occur.
- Third, the method does not compensate for intraframe smear. Algorithms to deal with blur within each frame are in their infancy and are simply not as good as having clean imagery from a balanced and stable gimbal to begin with. The processing demand to remove intraframe smear will far outweigh even that of interframe jitter compensation. Video latency will be a bigger concern.
- Fourth, automatic targeting recognition (ATR) demands that the image be as stable as possible. Multispectral and hyperspectral imaging with their multitudes of imaging bands are increasing target recognition accuracy and are hardened against countermeasures. Software stabilization applied to the data of hundreds of spectral bands would unnecessarily overwhelm processor time, whereas balancing would ease the need. Naturally, as new technologies evolve, methods for accomplishing software stabilization will become more efficient.

When considering your stabilization budget, balancing will affect most linear error sources in a proportionate way. Fixed errors should not be affected by balancing.

Stabilization systems that are sufficient for today's needs will feel increasing performance pressures. For cost growth control it is desirable that existing EO/IR systems (or any other sensor platforms) be capable of life-extension upgrades. Simple concepts come to bear here.

- If the camera is upgraded with a lens assembly of twice the effective focal length, the stability system now is required to halve its total error to make full use of the lens improvement.
- If the camera's sensor from the above example is later upgraded to one with twice the original resolution, the stability will need to increase by a factor of four over the original design. All refit gimbals should be pulled from service and rebalanced whenever a component is replaced. The mass of the removed/replaced components and the hole tolerances dictate the degree of unbalance that will occur if not rebalanced.
- Upgrades to a missile's propulsion or maneuvering system will place additional demand on the inertial stabilization loops.

Balancing offers a cost effective way to "upgrade" legacy systems. Medium accuracy applications will achieve of that of high accuracy, and high accuracy systems will surpass previous performance levels. Balancing hardens the system from the effects of unanticipated events. Another way to save cost is to create common assemblies which can be used in multiple applications. The smaller the gimbal package, the more likely it is that the gimbal can be used in multiple applications. Balancing becomes another tool in a designer's arsenal that enables more compact gimbal assemblies through decreased demand on the pointing and stabilization components.

Balancing is universal and works well with isolation techniques, gyro stabilization, and software stabilization, to enhance performance, to squeeze out what remains, and reduce the burden from these synergetic technologies.

11.0 Trends in Sensor Technology

Through the discussion of visible imaging, we have established the fundamental relationship between resolution and balance. Other types of sensors and sensor suites follow the same rules as outlined for staring focal plane arrays. Each has it own concerns and emerging technologies are pushing the resolutions higher and higher. Gimbaled platforms that were suitable for old technology may not perform adequately at current criteria and the future will hold even tighter performance specifications.

The need for increasingly stable platforms is driven by the desire for higher resolution.   Higher resolution sensor data ensures that the task at hand is completed successfully. The desire also drives technological advances in the sensors themselves. Once a new package has been put together, its success kicks off the next level of advancements. New sensors require platforms stable enough to take advantage of their enhanced performance; new performance levels drive the desire for better sensors, and so on.

Sensor information can be used for many purposes including:

- Real-time video surveillance
- Intelligence imaging
- Camouflage and concealment detection
- Bomb damage assessment
- Mapping
- Automatic Target Recognition (ATR)

Each purpose has its own set of tools and relies on specific sensor suites to complete the mission. Sensor suites are combinations of different sensor types that are co-boresighted and mounted on a common gimbal platform. Current types continue to evolve and new technologies are always under development. Let's take an abbreviated look at where this technology is heading and how gimbal balancing requirements will move with it.

Imaging – Visual band and IR

CCD arrays remain the dominant sensor for visual use. They operate in the 400nm-700nm band and offer high quantum efficiency, in a low cost front illuminated device. They are characterized by low noise and usable sensitivity extending into the near IR. Transition to HDTV type resolution in a full-frame device is underway. Recent improvements in quantum efficiency (QE) and signal to noise (S/N) characteristics permit the use of longer focal lengths in spite of less available light flux; and do so at true video rates. Longer focal lengths equate to higher magnification and place more burden on stability.

CMOS has held the promise of high resolution at low cost. High speed CCDs are limited by readout noise which increases proportionately with readout speed. Since CCDs are read out in serial fashion, higher resolutions would dictate faster readout rates in order to maintain the same frame rate. Their serial nature results in conflict between resolution and frame rate unless expensive multi-amplifier and processing solutions are implemented. CMOS sensors are not serial like CCDs; rather they are read out analogous to parallel. This supports both high frame rates and high resolutions. Early implementations of CMOS did not perform well enough to find widespread use in critical applications. The JPL developed CMOS APS (active pixel sensor) is opening the door to higher resolutions. These new breed CMOS sensors have lower noise characteristics and feature area of interest framing and overall faster frame rates. CMOS APS sensors improve every year and have found their way into some critical applications. The principal consideration for our purposes is that of resolution. The coming resolution improvements will require additional effort toward platform stability.

IR FLIR MWIR LWIR sensors detect thermal emissions. Of various and evolving constructions, they have the ability to see at night. Through the use of various wavelength IR bands, they have the ability to help distinguish exhaust plumes from diversionary tactics. Focal plane arrays are replacing scanning arrays and should continue to do so as the price comes down and performance levels rise. Two driving forces are pushing development. One is the need for higher resolution, and the second is the development of sensors that do not require additional cooling. In general, developers are pushing the interpixel spacing dimension lower while keeping noise trade-offs to a minimum. Of course, the resolution increase will push the same need for improvements in ancillary equipment as in their visual counterparts. Cooling traditionally is used to keep noise levels down. Uncooled IR sensors are more affordable and eliminate complicated plumbing and thermal management. As performance levels progress toward that of their cooled counterparts, sensitivities will increase, permitting their use at longer focal lengths and create the need for lower LOS jitter performance.

RADAR to MMWR (millimeter wavelength) – continuing advancements in millimeter radar (MMWR) technology has opened the door for microwave-based imaging seekers that are usable under adverse weather conditions which could stop a visual or IR system from working. MMWR's shorter wavelength yields increased resolution. Systems sufficient for older designs and resolutions will need to upgrade as higher resolutions necessitate less jitter. Although the amount of jitter correction required is less than that of high-resolution optics, the amount of tolerable jitter follows the same rules of resolution as above.

SAR (mechanically steered applications) – synthetic aperture radar through use of precision timing and sophisticated processing, SAR uses multiple RF pulses, and the aircraft's forward motion to create an artificially larger 'dish'. The apparent larger dish gives the SAR better resolution. The resolution is high enough to paint a detailed picture similar to a visual image.

SAR offers cloud-penetrating, all-weather performance. Critical timing concerns (driven by the synthetic aperture process) require the utmost in gimbal stability. The trend over the last decade has been for resolution to double every six years. Although this trend may not continue at the same pace, there still will be increased pressure on stabilized gimbal performance.

LASER designators – targeting and guidance. While engaging hostile targets it is desirable to increase standoff ranges. Conversely, it is also desirable to decrease the power expended by the laser. Aside from the weight savings of the laser itself, the laser will require smaller, less complex support equipment. Longer standoff ranges in combination with lower power, dictates a lower permissible jitter from the gimbal. Lower jitter will achieve higher deliverable power on target.

LIDAR/LADAR – 3-D imaging, the optical equivalent of RADAR. The use of laser pulses sent on target and gated sensors adds a third dimension to the created image. Time-of-flight critical timing places a premium on jitter control. Gimbaled scanning mirrors and area arrays are under continuing development.

LIDAR – spectroscopy - laser is used for remote illumination/excitation of aerosol clouds used in conjunction with various detectors. Scanning mirror induced laser jitter limits the effective range.

Mulitspectral/Hyperspectral imaging share all the same concerns above, but, the vast data-content will bog down processing. Stable imaging platforms will allow for cleaner merging of content into a meaningful display. Less initial jitter will free processing resources.

Numerous combinations and variations of these and new technologies are under development or are already in use. It is a safe bet to say that the technological advancements in all sensors will yield higher resolutions in the future, and that methods for pointing used now will have to mature with them.

12.0 Applications and Balance

The chart below is an exploration of applications and their possible primary interactions with gimbal balancing. By no means is it meant to express any hard limits.

Shaded Cells signify interactions of primary merit.

	Speed	launch G's	maneuvering G's	mass budget	power consumption	vibrations	shock	high zoom
Missile	fast	high	high	critical	yes	no	no	no
Large UAV	med	no	no	yes/no	maybe	no	no	yes
Small UAV	med	?	no	critical	yes	no	no	no
Helicopter	slow	no	no	no	no	high	no	yes
Marine	slow	no	no	no	no	high	yes	yes
Ground Vehicle	slow	no	no	no	no	high	yes	yes
Telescope	no	no	no	no	no	yes	no	yes
UCAV	yes	yes	yes	maybe	no	yes	no	yes
Fighter Aircraft	yes	no	yes	maybe	no	yes	no	yes
Missile Defense	yes	yes	yes	yes	yes	no	no	yes

About Gs, vibration, and shock: The three terms are different ways of saying the same thing. They are described differently here so as to offer better understanding for each application.

12.1 UAV

The operational environment:

- Extremely diverse, ranging from the turbulence free ride at 60,000 feet on-board a Global Hawk, to low altitude over hot deserts in a micro UAV.
- Principally, propulsion induced forces, wide spectrum turbulence, maneuvering forces, and structural vibrations define the environment. (Note: Within the scope of this document, it is difficult to do more than generalize.)

UAVs are tasked with the Dull / Dirty / Dangerous missions, such as long dwell time, hazardous environments, and over hostile territory. They are the remote eyes and ears, gathering information in situations where the risks for human pilots are deemed too high. Except for the few weaponized platforms; carrying sensor arrays is the reason UAVs are around, and consequently the reason the imaging quality and quality of other sensor data is considered paramount. The DOD periodically releases Roadmaps to UAV development. From these it is clear that there is no single “silver bullet” area of technology that will singularly advance to meet all the future goals. Every aspect of these aircraft will continuously “push the envelope” as the craft evolve. To this effort, USA expenditures by 2010 are expected to be 4.2 billion. Payload costs are approximately $8000 per lb. Typical UAV payload mass fraction is between 10 – 20% of total mass.

What Balance can do to help improve the situation:

A. SWAP – Size Weight Power reductions – the driving force in today's effort.

- Better balance enables engineers to design lighter/smaller gimbals through smaller torque motors. This in turn helps control vehicle mass growth.
- Greater operational range, fuel dependant - Balanced platforms require minimum unbalance ballast mass, reducing overall mass. Lower overall weight means less fuel is required for launch and maneuvering.
- Less track-loop and inertial rate-loop correction power expended – greater power reserves for other functions – less battery storage or generator mass is required.
- Loiter time over target is improved since energy consumption and overall mass are reduced. This in turn provides a greater opportunity for encountering subject and gathering information. Additional loiter time offers…
    - Opportunities to beat atmospheric conditions - to seek favorable turbulence zones based on terrain/weather models
    - Increased Target Detection Probability - better target identification accuracy at longer ranges.
    - Better maneuvering so as to view target from more aspect angles
- For electrical propulsion UAVs the power savings is one to one (power allocated to gimbal steering vs. power allocated to propulsion).
- For petro-chemical UAVs the savings are even more because gimbal electrical power conserved (battery weight or generator) means that propulsion fuel can be added at a greater energy density.

B. Improve MTBF (working life) and predictability

- Torque motor burnout due to power peaks stabilizing unbalanced gimbals is reduced
- Balancing creates power consumption predictability that maintains a level of isolation from conditions encountered – i.e. a balanced gimbal requires little correction current under all levels of turbulence, thus has very predictable requirements throughout the mission. An unbalanced gimbal requires radically different amounts of correction current under widely varying conditions.

C. Allow Higher Quality Imaging

- Only stabilizing method independent of frequency response – "balanced is balanced" at all frequencies.
- Greater standoff range through higher magnifications and/or simply more stable image at old magnification levels
    - Increase in standoff range eases potential political ramifications – air space concerns
    - Better balance yields higher stability enabling longer slant ranges to utilize higher zoom levels.
    - Lower the UAV's chance of detection by undesirables
    - Cost savings through lower attrition rates
- Minimize cross coupling (POI) slewing or vibration errors
- High resolution increases the probability of mission success

- Increase outcome success rate on actionable intelligence - Shorten response time from detection, to identification, to final response
    - Clearer imagery - Protecting the lives of friendly forces
    - Clearer imagery - Protecting lives of non-combatants mitigates political ramifications
    - Allows for efficient Border Patrol, helps prevent infiltration
    - Improve probability of Search and Rescue success – life and death stakes
- Increased input data certainty for autonomous algorithms such as flight navigation, detection, and targeting.

D. Data Bandwidth

- Eases communications bandwidth constraints - Better data transmission compression ratios for RF bands –
- High stability gimbals are an enabling technology for laser LOS communications

Future Outlook:

- Smaller packages are more modular for refit into other applications. Enables better cross platform compatibility, higher cost savings though refits and upgrades, and promotes end of life extension programs. These offer advantages to both the end user and the manufacturers.
- Future advances in emerging technology sensors suites. – Higher resolutions will mean more demanding stability needs, longer ranges, etc
- Goal for next 5 years is 40% improvement in endurance (see benefits above)

12.2 Rotary Wing Craft – Helicopter and UAV

The operational environment:

- Rotary winged craft operate in a vibration laden environment. In-flight data recoding provides the most accurate means of profiling this. Vibration levels are broadband random with narrow band peaks centered at several frequencies, the most significant of which is the main rotor blade passing frequency. This is generally in the 10-20 Hz. range. The overall G value (rms) is on the order of 3G. Secondary forces come from gear mesh noise, turbine engine rotation, and tail rotor and drive. The vibration environment of surveillance pods is somewhat harsher still.

- Static G levels caused by maneuvering and/or turbulence are about 5.5G maximum. Obviously the static forces in low turbulence vary greatly depending on flight maneuvers with no sizable static forces at hover, 0.4G peak in level flight, and 1G during an unremarkable transition from the forward direction to hover.

The stabilization hardware must be able to handle both the static G due to maneuvering and the vibratory G present in the airframe. Stabilization techniques are effective in the range of 0-200 Hz and for rms G amplitudes greater than 2G. Simple spring suspended isolators with appropriate damping devices should be able to handle the higher frequency vibration, although this will require the active stabilization to correct for any low frequency deflections and resonances in the spring suspension and isolation.

Obviously balancing the gimbal will reduce the demand on the active stabilization system and allow it to absorb larger perturbations without loss of control. Normal usage of very long focal lengths places a very high burden on the required stability.

What balance can do to help improve the situation:

- Ability to maintain longer standoff distances protects assets.
- Clearer imagery allows for positive I.D. of suspects, combatants, or targets.
- SAR - greatly increased probability of victim detection during Search and Rescue Ops saves lives. Allows for more efficient search patterns.
- Clearer image allows a larger field of view which reduces search time and/or increases area searched per hour

Future Outlook:
Advances in sensor resolution and new forms of sensors will continue to push stability requirements forward.

12.3 Missile

The operational environment

- Launch forces vary depending on the method used.
- Small missile vibration and maneuvering environment exceeds 50 G's.
- Large missile components are "controlled technology". This limits exportable technology to less than 10 G rms. From this we safely conclude that USA large missiles routinely experience higher accelerations.

Questions you need to ask:

- Is the target highly agile - i.e. 9Gs? Then large off bore-sight angles are required. Fast slew rates obtained. Seeker must pull 5 times the intelligent and motivated target's escape Gs to obtain high kill percentage.
- Is your gimbaled seeker pulling between 40-50 Gs in a turn? - Every 1 g-cm of static unbalance equates to 40-50 g-cm during maximum pursuit.

Lock on before launch adds to performance demands.

What balance can do to help improve the situation:

- Balanced gimbaled assembly ensures lock on target will not be lost during launch and maneuvering.
- Agile targets require fast gimbal slews. Balance-solution to track residual POI (to reduce cross coupling error) is necessary.

- Better balance yields higher jitter stability for E/O, Imaging IR seekers.
- More efficient search modes for acquiring the target.
- Fewer burdens on jitter compensation systems.
- For both within visual range and BVR (beyond visual range), higher stability means going autonomous from greater engagement range. Fire and forget from safer distances.

Future Outlook:

Successful intercept of future UCAVs will place higher burden on all aspects of seeker performance – including balance.

Higher accuracy gimbal balance machine supports future upgrades/refits – Extend the operational life of weapons systems by allowing for future advances in emerging technology sensors suites.

Higher resolutions will mean more demanding stability needs, longer ranges, etc.

12.4 Fixed Wing Craft

The operational environment:

- The maximum peak G load imposed on an agile aircraft fuselage in normal operation is 13G. The maximum peak G load imposed on any part of an agile aircraft in normal operation is 17G. This needs to be considered because the gimbal could be pod mounted on the wing. The loads on other military aircraft are 6.5 G and 7 G respectively.
- Vibration may cause in broadband G levels of 9.8 G rms over the frequency range of 10-2000 Hz. External and internal sound can also generate vibratory G forces, but they are generally lower near the nose where sensors gimbals are commonly found. Again, pod mounted sensor arrays will be subject to higher forces.
- Aerodynamic turbulent flow around the aircraft is common source for vibration. Boundary layer effects are small
- Little is coupled mechanically from the engine – most engine effects are acoustical 2-3 G rms
- Weapons launch may cause high forces shock/vibration depending on the technique used.

This vibration and g environment will affect gimbal-mounted sensor performance. The amount of degradation will depend on the mass and moment of inertia of the gimbal moving structure, the stiffness of the gimbal control system, its frequency response, and the various components of static and dynamic unbalance present in its structure. It is possible that static g levels will be adequately compensated for by the gimbal controller depending on the effective focal length of the system (imaging) or the RADAR or SAR equivalents. It is highly unlikely that the control will provide sufficient error correction for a vibration spectrum that goes out to 2000 Hz.

Balancing Advantages and Future Outlook:

- Manned Aircraft

- Multisensor RADAR and imaging sensor suites mounted in the nose consist of large heavy assemblies requiring higher resolution acquisition with every new generation suite or upgrade.
- Multiple sensor arrays are mounted on common platforms. Jitter control is required to be sufficient for highest resolution sensor in the group.

- UCAV – Unmanned Combat Aerial Vehicle – faster, more maneuverable than current manned high-agility air superiority fighters

    - In some respects, UCAVs will require ever advancing sensor suites to compensate for the missing decision making capabilities of human pilot.
    - Greater balance burdens will be placed on existing sensor platforms that are incorporated into new UCAVs. Perhaps the balance criteria thus far has sufficed for the lower performing human piloted craft, but will be under-corrected considering the higher g loads of the UCAV.
    - UCAV specific new gimbal designs will be subject to the same, more stringent criteria.

12.5 Marine Surface Craft

The operating environment:

- Measurements were made on a MKV Special Operations Craft in water with sea state 2.5 (3.0 ft significant wave height). Acceleration levels were measured at the coxswain's station; they would have been significantly higher if measured at the bow. Vessel speed was 35 kt. The largest peak acceleration of 8.6 g was measured when headed directly into the waves. This test also showed vibratory accelerations of 0.44 g rms over the frequency spectrum of 1-400 Hz.
- Other sizes and types of ships will exhibit different acceleration and vibration effects; the small, fast ship in the above example should probably be considered a worst case. From small craft to the largest, the ability to point and lock onto communications satellites represents another challenge.
- Larger ships in calm seas have less than 0.1 g's peak, with some roll angles and pitch angle concerns.
- Larger ships in heavy seas have low freq @ 1 g peak, and also have significant roll angles and pitch angles.
- Small craft moving slow in various seas have significant roll angles and pitch angles

A gimballed sensor assembly mounted higher on the ship's structure, somewhere in the middle of the ship's length, would experience significant amplification of the accelerations due to roll and pitch. Vibration due to the operation of the ship's propulsion unit and machinery would also be present and likely amplified in certain frequencies by the hull and superstructure.

What balance can do to help improve the situation:
The shipboard acceleration and vibration environment does not seem all that different from fixed or rotary wing aircraft, so the same arguments for balancing the gimbal should also apply here.

Future trends:
In the past, heavy sea states self-limited the demands on gimbals. Heavy sea states were normally equated to poor weather with poor visibility. However, in the age of imaging radars and multi/hyperspectral sensor suites, heavy seas and poor weather will become less of a limiting factor.

12.6 Other Applications

Ground Vehicles

The operational environment:
Tracked vehicles are subject to shock environment up to 8 G peak and vibration primarily at the track patter frequency of up to 6 G peak depending on terrain and speed. The track patter frequency with harmonics varies with speed up to about 500 Hz. Vertical jolts are the most severe. A moving Armored Personnel Carrier can have 0.5 - 3 G's rms.

What balance can do to help improve the situation:
Stabilized gimbals are used to mount many of the optical targeting systems. It is necessary that the vehicles fire on-the-fly under battle conditions. The environment can be quite severe, rivaling that of the other applications covered so far. Vehicle suspensions can absorb some of the force until bottomed out where it will rise dramatically. Balancing will help in all the ways described previously.

Missile Defense – Directed Energy Weapons

Operational Environment
The aircraft will likely be flying at 40,000 to 50,000 foot altitude, so it will be above most weather and turbulence. Most of the mechanical noise present will be the result of vibration from engines and onboard equipment. Static G forces will possibly be present due to maneuvering the aircraft.

General Comments and Future Outlook:
A hard push to reduce mass is underway. The system uses a gimbaled turret mounted on the aircraft's nose. The turret contains mirrors and other optical elements to allow the laser beam to be directed over a wide angle from the aircraft's path. The target missile may be several hundred miles away, so it will be necessary to stabilize the turret to focus the energy tightly. In order to minimize weight, it will be important to balance all moving parts.

Stability and aiming accuracy will have to be within 0.1 meter over a distance of several hundred miles to the target. The target must be tracked to this accuracy for at least several seconds as its azimuth, elevation and range are constantly changing.

D. E. Weapons may also be mounted on ships or land based vehicles, where the range to the target will be smaller (several tens of miles), but the vibration, g force and shock environments will be more severe. It will still be desirable to balance any gimbal structures in these cases in order to reduce total system weight and volume. Extremely high precision pointing accuracy required. For example, at 800 miles with one foot pointing accuracy, the gimbal needs to point with 0.048 arc-seconds accuracy or .25 uRadians (not necessarily a real case).

Missile Defense – stabilized gimbal seekers are pivotal to obtaining the incredible performance goals of the intercept vehicle.

Airborne Telescopes – higher jitter stability needed – balancing is a key technology to achieving it.

Guided Bombs and Projectiles use imaging visual and IR FPA – stability concerns are dictated by performance demands.

13.0 Conclusions

We have looked at numerous examples of gimbal mounted sensors of many types and the conditions which lead to degradation of 'image' quality. In particular, we have gone into considerable detail regarding the quality of optical images and the effect of external acceleration and vibration on the image quality.

There are many conditions which can degrade image quality including the components of the optical system and its position controls.

The first conclusion we must draw for a gimbal mounted optical system is that the optimum image quality for a given sensor, lens, image processor, and positioning servo control system is obtained when the gimbal is locked (caged) and the vehicle is stationary. That is, the best image is obtained in the absence of external vibrations, acceleration, or motion.

Since any real application for a gimbal mounted imager is unlikely to be stationary and vibration free, we can attempt to optimize the image in a number of ways.

The one method which reduces the effect of vibration and other accelerations and does not add a weight penalty is to balance the gimbal. Balancing ***always*** acts to improve the image quality regardless of the type of sensor, source or magnitude of external accelerations, type of control system, or inherent quality of the imaging system. Gimbal balancing has the added advantage of potentially reducing the required total mass and/or increasing the payload.

For the most critical applications, a 4-step balancing program should be used starting with design. It should be noted that if balancing is not a design consideration, balancing the gimbal after final assembly may not be possible.

1. Design considerations
    a. The individual bearing mounted gimbal assemblies should be designed with a goal of zero static and dynamic unbalance.
    b. The frames of the bearing mounted gimbal assemblies should be designed with locations for mounting ballast. A few good locations are vastly better than many random locations.
    c. The ballast locations must be easily accessible after final assembly ***without removing*** any moving components.
    d. Small sliding or thread mounted ballast weights should be considered for final trim balance.
    e. Wiring and plumbing routes should be planned to minimize the unsupported mass while allowing the gimbal to rotate freely
    f. Weight and CG specifications should be developed for all major components to minimize mass properties variation due to manufacturing and from vendor to vendor
2. Preliminary balance of major sub-assemblies
    a. For applications involving high slew rates and multi axis gimbals, dynamic unbalance (POI) and static unbalance (CG offset) should be measured on the moving sub-assemblies. POI measurement is often impossible after final assembly.
    b. Estimates should be made of the mass properties of wire bundles and piping. These should be added to the measured unbalance to determine the true unbalance as accurately as possible.
    c. POI and Static unbalance should be corrected.
3. Gross balancing of the final completed assembly.
    Gross balancing can be done if there are relatively few ***good*** ballast locations and relatively large ballast masses. This presumes that a final trim balance will subsequently be performed.
    a. Static unbalance should be measured.
    b. Static unbalance should be corrected in such a way that the addition of ballast does not add POI to the assembly. This may require more total ballast mass than would be required without POI consideration. It is a judgment call which is the more critical requirement, low total mass or minimal POI.
4. Final balance
    Final balance may be obtained using fine ballast weights or pre-positioned thread mounted ballast. In the end, unbalance should be measured to an accuracy ***at least*** 3 times better than the allowable static unbalance tolerance.

a. Fine ballast should provide moment increments of less than ½ the unbalance tolerance. This may require locations not previously permitted for gross balance.
b. The residual unbalance from gross balancing should be limited so the amount of final trim ballast is small enough so POI can be ignored.
c. Pre-positioned thread mounted ballast has several advantages.
    i. The total gimbal mass does not change when the residual unbalance is corrected.
    ii. The amount of correction can be very carefully accurately controlled by using fine threads.
    iii. If weights are mounted on threads which are perpendicular to the pivot axis, the effect of moving the weight along the thread will, independently, affect only one component of unbalance.

There may be other ways to improve image quality but a proven method with no down side is to balance the gimbal to a level commensurate with the required image quality and overall budget.

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Astrovideo – video capture

Invitation for comments

Recognizing the pace of developments in the various disciplines covered in this paper, and the information protection concerning many applications, the authors invite corrections and comments to the original content. We see this paper as a document that will continue to evolve as technology progresses. Our hope is that nothing in this paper is incorrect or obsolete at the time of publication. If you, the reader, would like to contribute comments, please feel free open a dialog. Contact us through: www.space-electronics.com

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