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Three-Axis Image Stabilization With a Two-Axis Mirror

George R. Lewis

CAI, a Division of RECON/OPTICAL, INC.
550 W. Northwest Highway, Barrington, IL 60010

ABSTRACT

Long Range Oblique Photographic (LOROP) cameras must provide quality images at long ranges despite disturbances from the carrying aircraft. A method of reducing these disturbances is termed image stabilization, and usually consists of both passive and active mechanisms. Two-axis gimballing of a pointing mirror for the camera has proven to be adequate to provide three-axis image stabilization. This paper describes the technique and the equations governing the stabilization.

1. AXES ARRANGEMENT

LOROP cameras have long focal lengths, usually 66 inches or greater. They tend to be long compared to their diameter, usually aligned with the carrying aircraft's longitudinal axis, and look perpendicular to the aircraft flight path by using a mirror mounted at 45° to the camera long axis. Figure 1 illustrates this arrangement. The camera looks at the ground at a range dependent on the depression angle from the local horizon. The "true" horizon of the earth lies at a depression angle of 3° to 4° due to the earth's curvature and the aircraft altitude (30,000 to 55,000 ft).

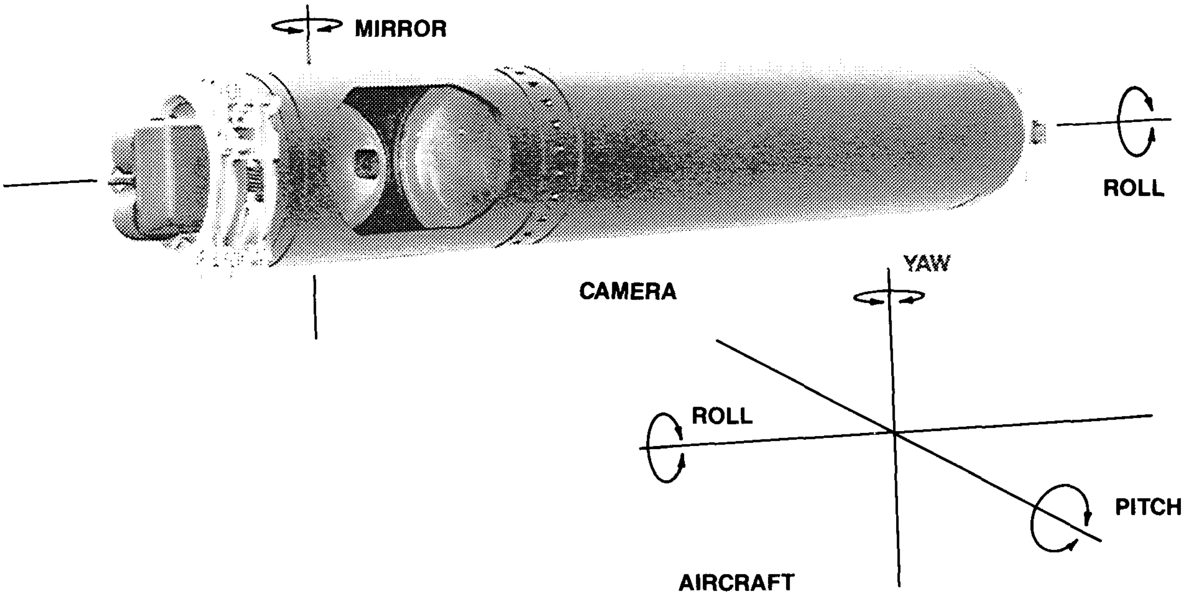

Figure 1 LOROP Camera Arrangement

The mirror, usually called a scan mirror, is mounted to rotate about an axis orthogonal to the camera roll (or depression) axis. One of its functions is to provide compensation for the aircraft forward motion (FMC). As the aircraft moves forward, the mirror rotates to maintain the scene image on the sensor during the exposure time. A rate gyro connected to the mirror axis measures the image rotation rate. The gyro-to-mirror connection lets the mirror move one-half the angle the gyro moves to allow for the angular doubling effect of the mirror around that axis. When the camera computer commands an FMC rate, the mirror axis servo drives the mirror until the gyro output matches the desired rate. The 1:2 coupling ensures the image rate equals the commanded FMC rate.

2. AIRCRAFT PITCH AND YAW EFFECTS

Figure 2 shows the orientation of the mirror axis relative to the aircraft pitch and yaw axes. The depression angle changes as a function of the range from the aircraft to the imaged scene. Figure 2 shows that any pitch and/or yaw disturbances are resolved around the mirror axis to give

$$dM/dt = \sin(D) * dP/dt + \cos(D) * dY/dt$$

where:

dM/dt = mirror axis angular rate
dP/dt = pitch axis angular rate
dY/dt = yaw axis angular rate
D = depression angle

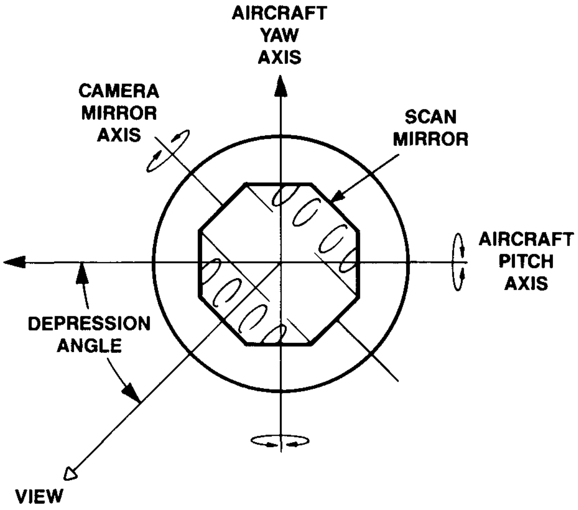

Figure 2 Mirror, Pitch and Yaw Axes

At a standoff range of 50 nmi from an altitude of 40,000 ft, the depression angle would be 7.9°. This results in the mirror axis rate gyro sensing the pitch and yaw rates:

$$dM/dt = 0.137 * dP/dt + 0.991 * dY/dt$$

The mirror axis rate gyro senses the aircraft-induced disturbances and sends these to the mirror axis servo. The mirror axis servo is configured to be a null-seeking loop with the error term trying to go to zero, so any disturbance appearing on the gyro output is reduced to near zero. Since servos have limited gain and bandwidth, the disturbances cannot be completely eliminated. However, the residual disturbances may be reduced to only 2 percent (or less) of the input disturbance. A 1°/s input disturbance (0.017453 rad/s or 17,543 μrad/s) at 1 Hz can be reduced to a residual image rate of 150 μrad/s. The linear image smear is

$$s = F * di/dt * t_e$$

where:

s = linear image smear (mm)
F = lens focal length (mm)
di/dt = residual vibration rate (rad/s)
t_e = sensor exposure time

A 150-μrad/s residual vibration rate will produce a linear image smear of 0.000070 mm for a 2800-mm (110-inch) focal length lens having a CCD sensor with a sensor line rate of 6,000 lines/s (an exposure time of 1/6,000 s). This image smear is equivalent to 0.006 pixel widths for a 0.011-mm pixel. For EK3414 film with an exposure time of 0.003 s, the image smear is 0.0013 mm or 1.3 μm. This is less than the film's granularity of 8 μm.

The power-bandwidth limits for servo amplifiers cause an increase in the amount of the residual vibrations as the disturbance frequency increases. To compensate for this, the camera is usually mounted in a passive vibration isolation arrangement. The passive isolation decreases the disturbances transmitted to the camera body as the frequency increases above any resonant frequency [1]. Because these passive isolators do not attenuate the disturbances below their resonance, the resonant frequency must be chosen carefully for the aircraft involved. Similarly, the peak disturbance amplification at resonance and the rate of attenuation above resonance must be controlled by carefully setting the passive isolator damping. Figure 3 shows an example of the passive isolator transmissibility, the active servo response, and the composite transmissibility for the LOROP image stabilization used with one system currently flying in several countries [2,3].

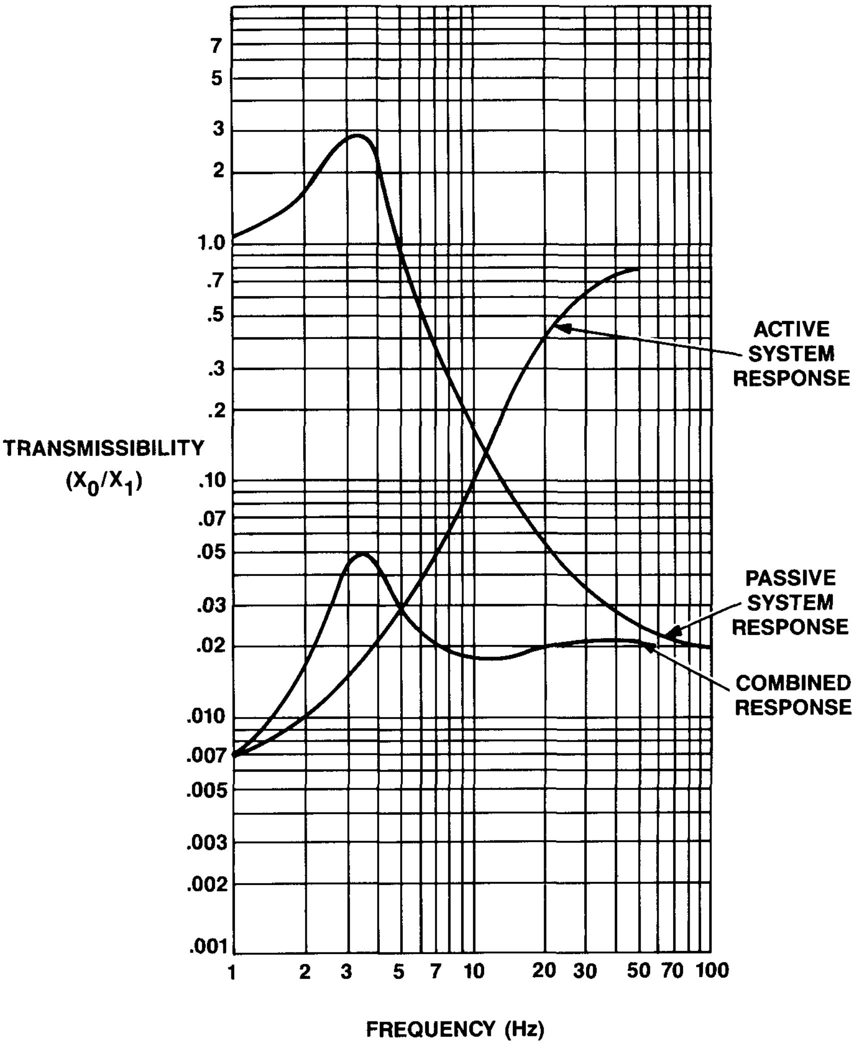

Figure 3 Transmissibility

Figure 4 shows the system effects of residual vibration for a specific case: 40,000-ft altitude, 30° sun elevation, 90° sun azimuth, 25-km ground plane visibility, 10:1 initial contrast and an average scene reflectivity of 0.15, for a standoff range of 50 nmi. At this range, the E-O system operates at the Nyquist limit, 45.45 lp/mm for the 0.011-mm pixel CCD. This happens until the residual vibration part of the smear Modulation Transfer Function (MTF) lowers the total MTF and causes the spatial frequency at which the Signal-to-Noise Ratio (SNR) = 3 to be below the Nyquist limit. The film sensor has no Nyquist limit, and the residual vibration reduces the total system MTF. This reduces the spatial frequency at which the system MTF intersects the film AIM curve, increasing the ground resolved distance.

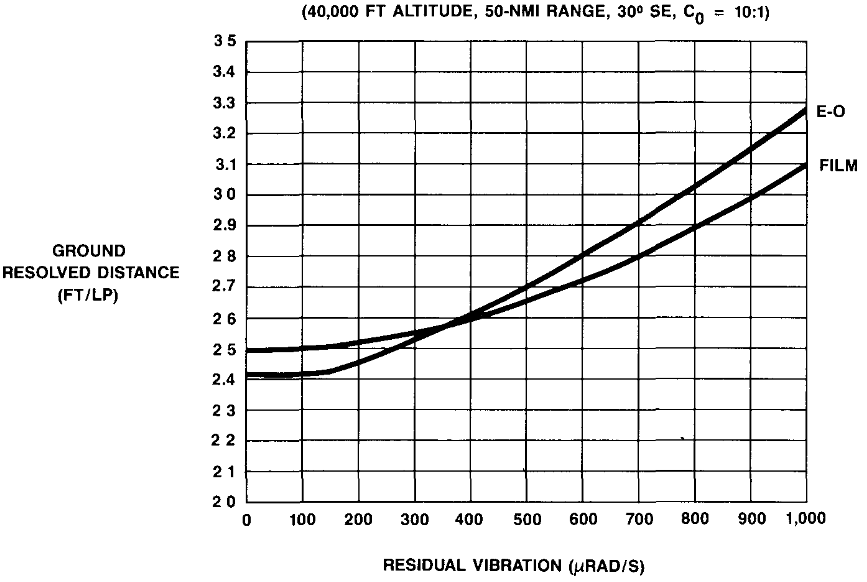

Figure 4 GRD vs. Residual Vibration

The effects of pitch and yaw disturbances not around the mirror axis can be easily determined. With the camera looking straight down, the mirror axis would compensate for the pitch axis motion but not for the yaw axis. The camera rotation about the yaw axis would produce an image rotation at the focal plane equal to the input disturbance. The image smear would then depend only on the image radius from the center of yaw rotation and the amplitude of the yaw rotation. The lens focal length does not enter into the effect. The pitch rate effects are similar. Using the example above, a 1°/s pitch rate would result in a 0.991°/s image rotation rate about the center of the image at the focal plane. At the edge of the sensor (2.25 mi from the center) and for the exposures from above, the film smear would be 0.003 mm (3 μm) and the E-O smear would be 0.0002 mm (0.02 pixels), which are negligible amounts.

LOROP film cameras using the two-axis stabilized mirror have been in constant use over the last 14 years. CAI's KS-146 camera (66-inch focal length, f/5.6) has produced in-flight resolutions exceeding 70 lp/mm for external or pod use. The same camera configured for internal aircraft mounting has consistently produced film resolutions exceeding 80 lp/mm, while operating at exposures of 0.003 s with EK3414 film. Figure 5 shows a 50X enlargement of an outer portion of a KS-146 picture. This part of the frame is approximately 120 nmi from the aircraft. The effectiveness of image stabilization with the two-axis mirror is shown here, as individual windows (1 m wide) can be seen in houses at 120 nmi (220 km).

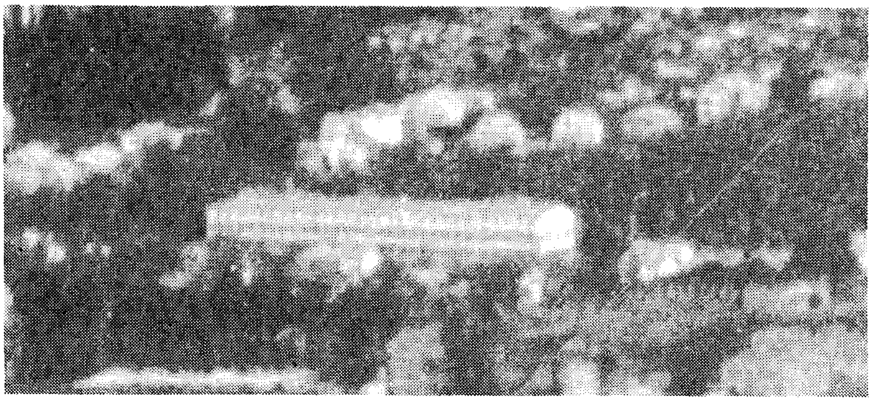

Figure 5 KS-146 Imagery

Three-axis stabilization would require mounting the LOROP camera in a gimbal assembly with three rate sensors and servos. Additionally, the camera assembly would have to be statically balanced about the pitch and yaw axes, and rebalanced each time any part of the camera had to be replaced during maintenance. Three-axis gimballing of a panoramic camera would start with the roll axis in the inside. Then the yaw axis gimbal would surround and support the roll axis. The outer gimbal would be the pitch axis gimbal so as to easily transfer the vertical loads into the aircraft structure. Figure 6 illustrates this type of camera.

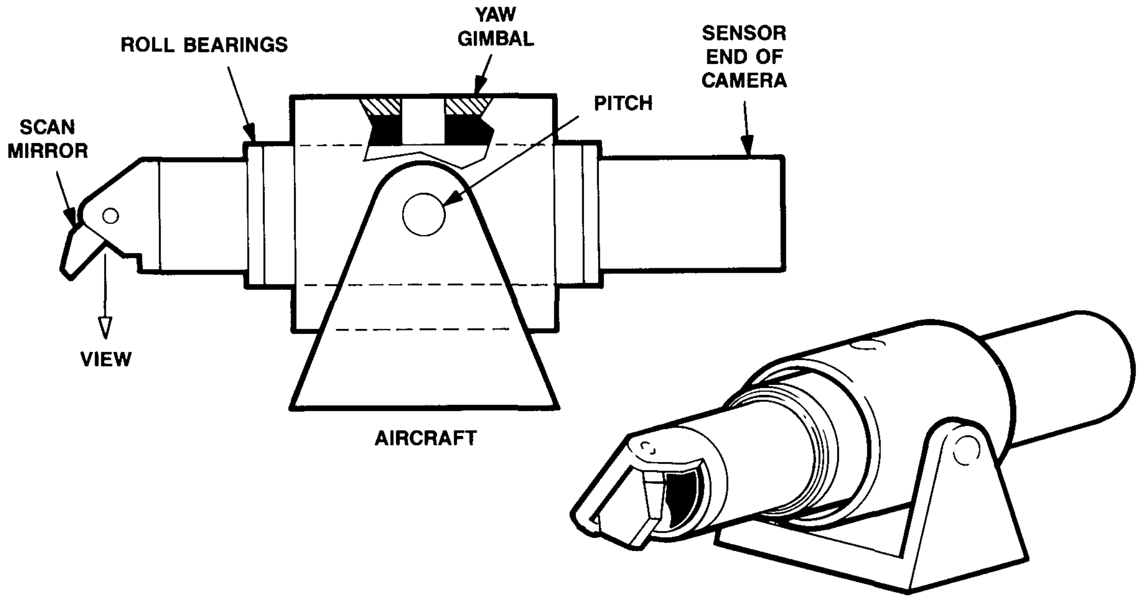

Figure 6 Three-Axis Stabilized Camera

Sufficient clearance must exist between the aircraft structure and the camera to allow for camera motion during aircraft pitch and yaw. If the LOROP camera were 100 inches long and pivoted at 50 inches, 4.4 inches of sway space must be available to accommodate a 5^0 pitch or yaw motion. The two-axis mirror stabilization technique needs only two rate sensors and servos, only 1 inch of sway space, and does not require balancing to the extent that the three-axis technique does.

Two-axis stabilization is a time-proven technique. It is used aboard ships and tanks for stabilizing gun turrets against vehicular motions to achieve their required accuracies.

3. SUMMARY

Two-axis image stabilization is a realistic, accurate method of improving image quality in LOROP cameras. This technique has been proven in LOROP systems in use for the last 14 years. The savings in cost, reduction in complexity, and improvement in reliability indicates that it is preferable to three-axis techniques.

4. REFERENCES

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