Technical Challenges For Small UAV Payloads

Payload engineers push imaging technology limits under constrained SWaP budgets and deliver stabilized full motion video from small unstable airborne platforms.

by Chris Johnston

The small unmanned aerial vehicle (UAV) marketplace has recently displayed dramatic growth in the variety of airframes and payloads. While large, familiar UAVs like Predator, Shadow, and Global Hawk garner much of the press and attention, small, unheralded UAVs deliver the majority of intelligence, surveillance, and reconnaissance (ISR) video and execute the bulk of sorties. The small UAVs are represented by micro-UAVs as tiny as a hummingbird, to UAVs that weigh 150 lbs and lift >10 kg payloads. Small UAVs are generally launched by hand, by an accelerating launcher, or are vertical take-off and landing (VTOL).

Payload engineers are always faced with limited budgets in terms of mass, volume, and power for small UAVs. In parallel, however, the same engineers are asked to deliver very narrow field-of-view images, exotic on-board image processing, lossless video compression, multi-color simultaneous imaging, and hundreds of other technically advanced attributes that are difficult to execute in a laboratory, let alone from a small aircraft buffeting in the wind. This article will discuss some of the high-level issues that suppliers and customers need to address when considering the delivery of video to the ground from a small UAV.

Figure 1: Hood Technology's 4-axis gyro-stabilized imaging system, Model Alticam 11 EO/IR.

Defining Small UAVs

Each branch of the armed services has its own definition of a UAV class, sometimes call tiers — Tier I, Tier II, and so on. There are names for UAV classes — small tactical unmanned aircraft systems (STUAS), mid-endurance unmanned aircraft systems (MEUAS), maritime tactical unmanned aircraft systems (MTUAS), and so on. The most numerous UAVs are small, hand-launched aircraft powered by electric engines. Typical flight endurance is 20 to 90 minutes, and typical operating altitude is hundreds of feet. The prevalence of these small, hand-launched aircraft is a testament to their value and effectiveness. Thousands of small, hand-launched UAVs have deployed with U.S. troops overseas. Payloads for these hand-launched systems are relatively simple, mostly fixed visible or thermal cameras mounted in the small airframe. Articulated payloads have only recently been introduced, and most payloads deliver limited functionality due to the strict mass and volume limits required for a hand-launched platform.

The next step up from hand-launched is the small, tactical unmanned airborne systems, or STUAS. These are typically liquid-fueled aircraft with mission endurances from 8 to 24 hours, weigh from 40 to 150 lbs, and have the capacity to lift heavier, more complex payloads. The team at Hood Technology (Hood River, OR) was involved in the early development of two STUAS platforms, the Aerosonde and the Scan Eagle. The Scan Eagle is currently a widely deployed small tactical UAS in the U.S. fleet. The first intended uses of these aircraft were varied, but they were universally promoted as small, long-endurance aircraft with missions lasting from 12 hours to several days. In the late 1990s, the Hood Technology team contributed to the first trans-Atlantic flight of an unmanned aircraft, crossing the Atlantic in 26 hours. This was achieved with 1.5 gallons of fuel.

An early approach was to develop useful aircraft and then determine what payloads were needed to generate commercially viable businesses. Early payloads ranged from weather sensors and geomagnetic sensors to cameras. After the first STUAS aircraft were flown and the flight attributes well understood, the trade-off between payload and flight attribute immediately ensued. Originally, it was a direct trade-off between payload mass and flight endurance. Simply put, for every gram of payload loaded onto the aircraft, a gram of fuel was removed, and the mission life was reduced. There are hundreds of surrounding complexities with the payload and its support, but mainly, it was a payload grams/mission duration trade-off.

The earliest missions for Aerosonde and Scan Eagle STUAS-class UAVs have not yet become commercially significant. Tuna boat captains envisioned using robotic airplanes to search for schools of tuna rather than conducting searches with helicopters. Long-endurance, geomagnetic mapping missions over the northern reaches of North America were conducted. Here, the long-mission duration favored the unmanned aircraft vs. the manned aircraft.

UAV Imaging Payloads — Design Factors to Consider:

- **Available budget: mass, volume, power**
- **Stability per unit — image integration**
- **Video interface, available wires**
- **Downlink bandwidth**
- **Mission duration, intended above-ground-level (AGL)**
- **Slant range (actual distance from the UAV camera to the target)**
- **Processing for image presentation, on-board or ground**

With a hat-tip to early developments of UAV technology in Israel, the U.S. UAV business accelerated dramatically with the military actions in Iraq and Afghanistan in the early- to mid-2000s, and the advent of UAVs for the task of intelligence, surveillance, and reconnaissance (ISR). In early cases, the best, most common use of a UAV was to deliver video ISR data to troops on the ground. Attributes mostly relating to video quality now drive the designs of most small UAV payloads.

Video ISR Payload

In military applications, the desired product is high-quality video ISR data that can deliver actionable information. What, then, is useful ISR video data? The most common requirement of any ISR video is to provide high-resolution pictures/video of ground targets. Manned surveillance aircraft always delivered high-quality images, but when captured from >5,000 feet, the resolution on the ground was never very high. Manned flight for ISR purposes over dangerous areas is expensive, hazardous, and relatively short in duration due to aircraft and pilot limitations. Small UAVs have been employed primarily in situations where endurance and close tactical support are required. Consider again the value of high-quality ISR. One can fly a cell phone camera on a small UAV 15 feet from a subject and have very high-quality video. But if that close-range, high-quality video modifies the subject's behavior, how valuable is the quality of the ISR? Most UAVs fly overhead undetected and deliver ISR data to decision makers without altering the behavior of subjects on the ground. The viewers of ISR data want very high-fidelity data, and in most cases, they desire stealth.

To complicate matters, consider what is needed to deliver narrow-field-of-view, quality video from a small aircraft. The platform is moving, vibrating, and subject to random and uncontrollable motion of the aircraft. The line of sight for the delivered video needs to point at the object of interest on the ground, hold on that object of interest while the aircraft is flying its course, and be immune to input disturbances that would cause the camera's line of sight to move. So the payload engineer is always combining the basics of imaging requirements with the science of vibration and disturbance rejection. In the small UAV world, we constantly struggle with issues of camera and lens mass/volume/power, the stabilized camera platform, and the requirements of video hold or track from a moving camera platform.

The UAV payload designer always returns to the primary issues involved in flying a robotic or remotely piloted small aircraft — mission length and fuel load vs. payload weight. Video quality is a fluid value — how good is the camera and how stable is the image. Fundamentally, the small UAV is used to observe small vehicle and human-scale objects on the ground. Much of the time, the design of an ISR payload is driven by the operating altitude, or aircraft above ground level

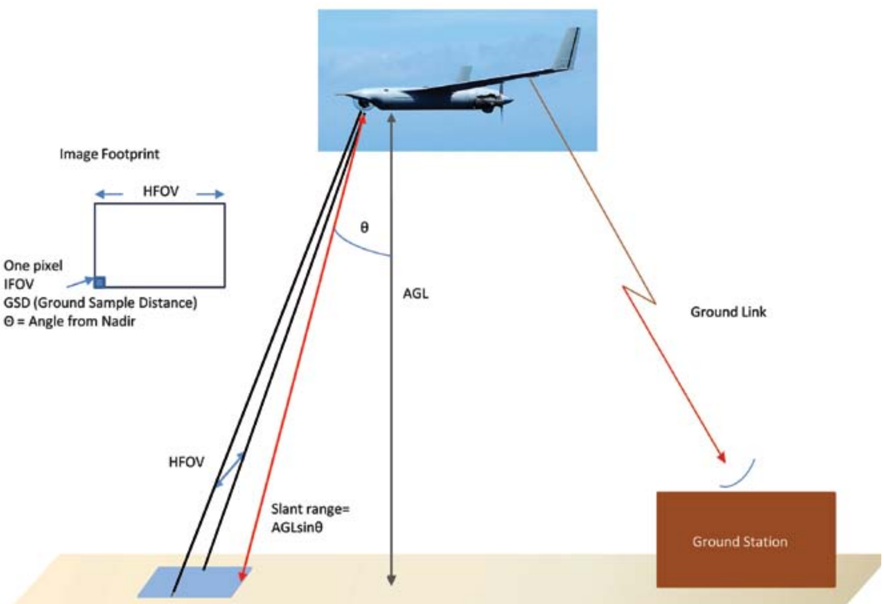

Figure 2: Glossary of terms for UAV imaging. AGL = Above ground level. HFOV = Horizontal field of view, the longer dimension of an imager's field of view. Slant range = Distance to target, product of AGL and the sine of the angle from nadir. GSD = Ground sample distance. IFOV = Instantaneous field of view, the angle subtended by one pixel, usually in microradians.

(AGL). So the payload designer is driven by the requirement to deliver a certain instantaneous field of view (IFOV), or the angle subtended by a pixel, and thus delivers a desired ground sample distance (GSD) from the operating AGL.

The AGL is determined by a number of factors. First is the optimum operating altitude for an aircraft. The smallest UAVs operate at hundreds of feet AGL. Some of these aircraft are stealthy, some are not. Other small UAVs operate at AGLs of a few thousand feet. In some cases, this is where operating doctrine allows unmanned aircraft to operate. In many cases, the altitude is determined by the point where the aircraft is visibly imperceptible from the ground, and there is low or no auditory signature. Ideally, all aircraft would be invisible, inaudible, have enough video zoom to count fingers, be perfectly stable, and operate day and night. Some would even argue for these attributes to be maintained while imaging through clouds. A fundamental fact of airborne imaging is that as fields of view get narrower and narrower, lenses get larger and heavier, and the requirement for precision stabilization and pointing increases. It is a simple calculation to estimate the stability requirement, or disturbance rejection requirement, for a given GSD and exposure time. For small UAVs, payload engineers need to design around lightweight, long effective focal length (EFL) cameras, thereby creating lightweight, effective disturbance rejection, vibration isolation, and pointing systems around these advanced cameras.

Next, there is the desired video quality, usually attributable to GSD. As of late, the scale defined by the National Image Interpretability Rating Scale, or NIIRS, has defined the ground distance a pixel must cover. NIIRS scales are subjective image interpretability and are independent of slant range. Simply put, the higher the NIIRS rating, from a given slant range, the greater the zoom, or the smaller the IFOV, or the smaller the GSD. From there, optical geometry will determine the sensor and effective focal length required to achieve a given GSD, and a predicted NIIRS rating (see Figure 2 on prior page).

The primary challenge of the payload engineer is determining the best, most rational, available camera technology and designing it into the stabilized turret. They sum the mass of the stabilized imaging system, determine the power required, ensure it will fly without too much surface drag, and deliver the best video possible to the ground. Challenges arise when the delivered ISR video data needs to provide more zoom.

Figure 3: Current capability of advanced stabilized EO UAV payloads. Narrow field of view image represents standard definition (SD) imagery with a 0.30 degree HFOV. All images captured at 3,000 meters using Hood Technology's Alticam 09 EO.

Currently, payload engineers are struggling with the conflicting requirements of high NIIRS value and fixed, limited payload mass. One can image very small objects from very great distances given an unlimited mass budget. A home astronomy telescope provides very high-resolution imagery of objects at many kilometers, but it is just not possible to lift a large diameter, heavy telescope, and then fly it to a target and loiter for hours. The payload engineer needs to find the best possible combination of optic and sensor to deliver the desired video result.

Imaging Payload Considerations

Three payload turret designs are discussed here: 1) high-performance, cost-effective EO visible imaging payloads; 2) high-performance, thermal imaging payloads; and 3) multichannel imaging payloads. The drivers in payload performance can be reduced to simple camera performance criteria and achievable stability per unit mass, volume, and power (see Figure 3).

EO

EO, or visible imaging, payloads have been dominated by simple block camera configurations available from large commercial suppliers. These suppliers have developed imaging modules for consumer, handheld camcorders and widely deployed video security systems. The overwhelming volume of units produced allows payload engineers to design around a volume-manufactured, tightly integrated, well-defined imaging unit. The cost to develop a custom camera system of equivalent performance is prohibitive for the marginal benefit in pixels, sensitivity, or EFL.

These commercial-off-the-shelf (COTS) visible imagers typically deliver NTSC video with a well-defined zoom range. With a given zoom, or FOV, we can accurately calculate GSD with a given AGL and slant range. A survey of typical EO payloads or EO channels will find a remarkable similarity in optical performance — due primarily to the supply of common COTS imaging modules (see Figure 3).

Newer EO imaging payloads combine COTS imaging modules for wide FOV imaging, high-definition cameras, and customized optical systems. The latest payloads provide GSD values of 1.0 cm from 4,200 ft. slant range. Combining the traditional block cameras side by side with customized imagers and optics, payload engineers have developed a dual sensor with HFOVs ranging from 54 degrees to 0.29 degrees, extending the NIIRS rating to 9+.

Thermal

Thermal imaging presents a significant challenge in small UAV payloads. Anecdotally, more ISR missions occur at night than during the day. EO payloads have tremendous performance, but they are blind at night, thus the pervasiveness of thermal imaging in the UAV payload world.

Infrared (IR) pixels are larger; the optics are also larger, less flexible, and heavier; and integration times tend to be longer than the exposure times for a typical EO imager in daylight — the longer the integration time, the greater the stability requirement. The natural instinct for the payload designer is to select a small, uncooled camera. Uncooled cameras are plentiful, inexpensive, lightweight, low power, and small — a payload designer's dream — until you consider the optics required for uncooled imagers. All uncooled imaging occurs at f/1.8 or lower; the lower the f/#, the larger and heavier the optic. The longest conceivable EFL for an f/1.5 optic in a small (20 kg) UAV would likely be 100 to 150 mm. For a slant range of 4,200 ft., this would translate into a FOV of greater than 4 deg. At this FOV, for standard definition (SD) imagers, one could suggest acceptable performance. But a number of other criteria make this a false suggestion. First, uncooled zoom optics are generally massive. Only recently have manufacturers introduced lightweight zoom optics for uncooled sensors. Uncooled sensors have long reset times (equivalent to exposure times), thus increasing the stability and disturbance rejection requirement. Given a camera that weighs less than 40 grams, an optic can still weigh greater than 1,000 grams.

In Figure 4, a photograph of two different imaging test fixtures for MWIR (left) and LWIR (right) are displayed. Both are continuous zoom optics including the latest sensor technology. The MWIR can deliver 55 µrad IFOV, while the much larger LWIR delivers 77 µrad IFOV. The entire MWIR assembly weighs nominally 1,100 grams, while the LWIR assembly weighs 4,350 grams. For a target IFOV of <100 µrad for reasonable ISR quality, the LWIR is nearly impossible to fly on a 20 kg UAV, simply because of size and weight, while the MWIR delivers better IFOV, shorter integration times, more sensitivity, and much lower mass and volume, despite the requirement of a complex Stirling-cycle cooler.

At a point, there is a clear benefit to cooled midwave infrared (MWIR) sensors. Intuitively, one would think a cooler, a cold shield, and all the associated electronics for a cooled integrated Dewar cooler assembly (IDCA) would be precluded from a small UAV payload because of the sensor's starting mass. Just the sensor, the IDCA, and no electronics or optics, costs nominally 400 grams. This starting mass is decreasing as new sensor technologies are introduced. The real benefit is realized at the optic. With f/#s as high as f/5.5, suddenly the payload engineer has EFLs approaching 300 mm at a mass of nominally 450 grams. Add electronics at about 40 grams, and a cooled MWIR camera can be considered at around 1,200 grams delivering NIIRS 7 or better from 1,300 meter slant range. Intelligent optical design keeps physical geometries within reason. Short integration times allowable with highly sensitive cooled sensors, and reasonable power requirements on the order of 6 to 8 W, add to an effective sensor with better performance and lower mass, even with the mechanical cooler, when compared with longwave infrared (LWIR) uncooled solutions.

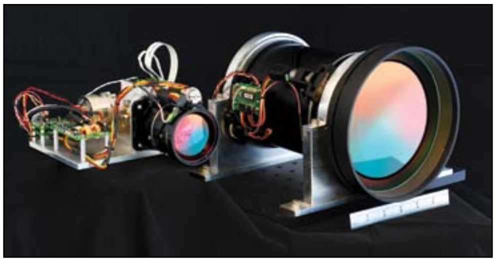

Figure 4: Sample test imagers representing the relative size and weight of MWIR (left) and LWIR (right) assemblies delivering <100 μrad IFOV performance necessary for quality ISR from typical, small UAVs.

Multichannel

Most airborne imaging payloads have more than one imaging channel. For example, designers often combine EO/IR for imaging, a laser pointer (LP), and perhaps a laser rangefinder (LRF). More channels can be considered: shortwave infrared (SWIR), low-light television (LLTV), laser markers, and laser spot trackers. Even more exotic sensors are around the corner — third-generation IR with multicolor pixels, small flash light detection and ranging (LIDAR), and hyperspectral imagers. The same design considerations apply. What is the slant range? What is the ground sample size? What is the mass budget, volume budget, and power budget (especially important when considering advanced laser applications)? Multichannel payloads for small UAVs will also need to address the issue of surface area available for windows.

A reasonable multichannel payload will have limited channels on small UAVs. The most common configuration will include EO/IR/LP/LRF. The EO, LP, and LRF can share windows. The IR commonly has its own window, silicon (Si) in the case of MWIR. Multichannel payloads will be dominated by the weight of the IR system, which in turn will likely be dominated by the weight of its optic. On the power side, the inclusion of the newest laser marker technology will impart a new power draw that requires tradeoffs. Multichannel payloads for the STUAS-class airframes start at nominally 3.3 kg and increase from there.

In conclusion, we've reviewed the challenges that are present when considering various payload options for small unmanned aircraft systems. The goal is to design and provide payloads that deliver the least mass, volume, and power draw per IFOV unit, which will result in the longest duration and the most cost-effective ISR missions possible. ■

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