

An Infrared Microsensor Payload for Miniature Unmanned Aerial Vehicles

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ABSTRACT

Miniature unmanned aerial vehicles (UAVs) are a category of aircraft small enough to be transported, launched, operated, and retrieved by a crew of one or two. The concept is not new, having been in limited use by the U.S. military over the past fifteen years, but interest in potential applications is growing as size and cost of the vehicles come down. An application that is particularly significant to the military and law-enforcement agencies is remote reconnaissance, with one or more onboard sensors transmitting data back to the operator(s) in real time. Typically, a miniature UAV is capable of flying a pre-programmed route autonomously, with manual override as an option. At the conclusion of the mission, the vehicle returns for landing, after which it can be quickly disassembled and stowed until its next use. Thermal imaging extends the utility of miniature UAVs to operations in complete darkness and limited visibility, but historically thermal imagers have been too large and heavy for this application. That changed in 1999 with the introduction of Indigo System's Alpha™ camera, which established a new class of thermal imaging product termed the infrared "microsensor". Substantially smaller and lighter than any other infrared imaging product available at the time, Alpha™ was the first camera that could be readily packaged into the nose of a miniature UAV. Its low power consumption was also a key enabling feature. Building upon the success of Alpha™, Indigo then took the microsensor class a step further with its Omega™ camera, which broke all the records established by Alpha™ for small size, weight, and power. Omega™ has been successfully integrated into several miniature UAVs, including AeroVironment's Pointer and Raven, as well as the Snake Eye UAV manufactured by BAI Aerosystems. Aspects of the Omega™ design that have led to its utility on these and other platforms are described, and future prospects for even smaller microsensors are discussed.

1. CHARACTERISTICS OF A MINIATURE UAV

A primary battlefield advantage of a man-portable UAV is the ability to provide remote reconnaissance on a moment's notice without directly exposing soldiers to an enemy. Because they can be operated by a small crew with little advanced preparation, miniature UAVs are well suited for scouting ahead of advancing troops to detect ambushes or potential obstacles. For military operations in urban terrain (MOUT), the situational awareness provided by a sensor flying above building level is a tremendous asset for optimizing troop deployment and avoiding unfavorable encounters with pockets of resistance. It is also feasible for a company commander to employ miniature UAVs to support patrols, perimeter surveillance, forward observation, and search & rescue operations. Yet another application is collaboration with unattended ground sensor (UGS) networks. After detection of an intrusion via a ground sensor, a miniature UAV can be quickly put on station in the vicinity of the detection to track the intruder beyond the sensor range of the UGS network.

Based on such applications of miniature UAVs, several key system requirements can be identified:

Easily Transported: To be utilized effectively by dismounted light forces, a miniature UAV must be man-portable. This requires that the system be lightweight, with “system” referring not just to the vehicle itself but also to all auxiliary equipment including the ground station, packing containers, and spare batteries. Minimum stow size is imperative; ideally, the entire system should be transportable by a single operator. The system must also be capable of quick assembly and disassembly to support rapid deployment / rapid evacuation.

Easily Launched. Another pre-requisite of rapid deployment is the ability to launch the vehicle with little or no advanced site preparation. For operation in confined quarters, such as in urban terrain, another critical aspect of getting the vehicle airborne is that it can be accomplished in a small launch area. Ideally, little or no auxiliary equipment is required for take-off.

Easily Operated / Easily Landed. For it to be practical for non-specialists to operate a miniature UAV, a key requirement is the ability to fly and land the aircraft with minimal advanced training. This requirement demands an auto-navigation system with autonomous capability to fly a pre-programmed route. Because landing is the most difficult aspect of operation, either a simplified landing procedure or an automatic landing capability is essential.

Reliable / Robust. For applications such as perimeter surveillance, it is critical that the system be capable of repeated missions flown virtually around the clock with little or no down time. This goal implies exceptional reliability. Furthermore, harsh landings and even crash landings are inevitable since the vehicles are intended to be flown by operators lacking advanced piloting skills. A robust, rugged design is required to withstand an occasional mishap. That said, the cost of the vehicle must be sufficiently low to be considered expendable, particularly since it is flown within range of small-arms fire.

Covert. To minimize detection and attack by an enemy, a miniature UAV should be stealthy. A small aspect is required for visual security, and audio security demands a quiet propulsion system such as an electric motor. A vehicle that must skim close to the target has a greater probability of being detected and destroyed than one with higher performing sensors able to operate effectively at higher altitude.

Long Range / Long Flight Time. The utility of the vehicle in many applications is directly proportional to its maximum range relative to the ground station. Target tracking, forward scouting, and perimeter surveillance are applications that are all more viable with long-range capability. Even for applications over a fixed site, such as situation monitoring, a long flight time between refueling minimizes gaps in coverage. Flight time is primarily limited by battery capacity and can be improved by minimizing drag, weight, and power consumption.

Payload Flexibility. The ability to incorporate multiple sensors into the vehicle enhances the utility of a miniature UAV system. Ideally, several sensors can be flown simultaneously. For example, a forward-looking imager can be used for navigation and search, and a side-looking imager can monitor the area of interest as the vehicle circles. Even if the aircraft can accommodate multiple sensors, the ability to swap payloads quickly and easily between flights is important. For example, during daytime operations, an operator may find a visible image most effective, but after dusk or when a battlefield becomes covered in smoke, he will want to install thermal imaging.

2. REPRESENTATIVE PLATFORMS

Pointer. AeroVironment's Pointer, shown in Figure 1, is a pioneer of the miniature UAV industry, having made its first flight more than seventeen years ago. It is a field-proven system that is still in active use by the U.S. military and various law enforcement agencies. Compared to more modern systems, its dimensions are relatively large – 2.7 m (108 in.) wingspan, 3.6 kg (8.0 lbs.). However, the complete system stows compactly into three portable containers that are easily carried by a crew of two. Set-up can be completed without tools in less than five minutes, and the vehicle is then hand-launched. (See Figure 2). Pointer contains an advanced auto-navigation system with a military-GPS receiver and on-board avionics to improve stability. A wireless link provides real-time video transmission with a nominal link range of 5 to 10 km (3 to 6 miles). To eliminate the need for a prepared landing strip (and advanced piloting skills), landing is accomplished via an automated intentional stall which produces a stable, controlled drop to the ground.



Figure 1: AeroVironment Pointer UAV



Figure 2: Hand-launch of a Pointer

Raven. Currently in advanced development at AeroVironment is another miniature UAV system named Raven, shown in Figure 3. It is roughly half the size of Pointer, 1.3 m (51 in.) wingspan and 1.8 kg (4.0 lbs.), with similar performance characteristics (see Table 1). Raven uses the same ground control station as Pointer and has the same four auto-navigation modes: altitude hold, waypoint navigation, auto-loiter, and fly-home. Pre-production Raven prototypes were first flown in October 2001 and are currently undergoing advanced testing.



Figure 3: AeroVironment Raven

Table 1: Comparison between Pointer and Raven

	Pointer	Raven
Link range	5 – 10 km (3 – 6 miles)	5 – 10 km (3 – 6 miles)
Flight speed	35 – 80 kph (22 – 50 mph)	43 – 96 kph (27 – 60 mph)
Duration	90 minutes	80 minutes

Snake Eye. The Snake Eye UAV system was developed by BAI Aerosystems to provide forward-deployed troops with capability to conduct area surveillance and force protection. The system is fully man-portable requiring only a two-man crew to deploy and operate. Snake Eye includes multiple sensor payloads, including daylight color, low-light monochrome, and IR imaging systems (see Figure 4), as well as nuclear-biological-chemical (NBC) detectors. These are housed in interchangeable nose assemblies that literally “snap” onto the fuselage. This allows Snake Eye to be reconfigured in seconds.

With a 1.2 m (48 in.) wingspan, the composite airframe of the Snake Eye weighs just over 2.5 kg (6 lbs) in the “ready-to-fly” configuration shown in Figure 5. The air vehicle includes battery-powered electric propulsion with up to 1 hour flight time and a 10 km (6 mile) range. The vehicle is practically inaudible when passing overhead at an altitude of 100 m (328 ft).



Figure 4: BAI Snake Eye Interchangeable Noses



Figure 5: BAI Snake Eye UAV

The Snake Eye UAV is intended to be operated with minimal training. The Ground Control Station (GCS) is housed in a small watertight case that runs off a SINCGAR-compatible (BA-5590/U) battery and includes a ruggedized laptop computer with mission planning and moving map software, high-resolution video goggles for real-time video display, and high-gain direction receive antenna, all shown in Figure 6. The aircraft is launched with a simple and reliable bungee launch system (see Figure 7). Once airborne, it flies autonomously using an in-flight-programmable GPS-enabled flight control system. The air vehicle also lands autonomously.



Figure 6: Snake Eye GCS



Figure 7: Launching the Snake Eye UAV

Over the course of hundreds of test flights, BAI’s Snake Eye has demonstrated exceptional durability. The modular design, with snap together components (noses, wings, fuselage, and tail), is highly robust since these components “shed” if the air vehicle strikes an obstacle during flight or landing. Vehicles have collided with trees, buildings, and vehicles and sustained very little damage. While the military considers this system to be expendable, BAI has found that damage to most Snake Eye UAVs has been minimal and mostly cosmetic, even for operations in unimproved areas.

3. ALLOCATED REQUIREMENTS TO AN IR PAYLOAD

Based on the characteristics of miniature UAV systems, several key requirements can be allocated to an infrared imaging payload:

Lightweight. One of the most important requirements for a sensor payload in this application is weight. A heavy sensor will disrupt the center of gravity, requiring ballast to be added to counteract the added weight in the nose. Weight of the payload and ballast detract from maneuverability, maximum airspeed, and flight duration.

Small size. For an existing vehicle such as Pointer, Raven, or Snake Eye, a candidate sensor must obviously fit within the space reserved for the payload or else it cannot be included. Even when there is flexibility for accommodating a sensor (e.g., on a conceptual vehicle design not yet completed), small size is imperative because of the implications on drag characteristics. The same parameters affected by weight – maneuverability, airspeed, and flight duration – are generally affected even more so by drag. If vehicle size grows to accommodate a large sensor, performance will be sacrificed. Another compelling advantage of a small sensor is that it offers more potential for a multi-sensor payload (e.g., forward- and side-looking).

Low power consumption. Minimizing power consumption of an on-board sensor reserves more battery capacity for the aircraft's propulsion system and wireless link. A low-power thermal imager thus contributes to longer flight duration and longer range.

Standard interfaces. To facilitate sensor swapping (e.g., thermal for visible), the use of standard interfaces is critical. Simple "power-in, video-out" operation of a thermal sensor promotes a straightforward interface to other onboard electronics, especially if the sensor is capable of operating directly off the vehicle battery. A standard video protocol, such as NTSC, is far more preferable than a custom video signal.

Ruggedness. For a vehicle such as Pointer, landing is accomplished by stalling the vehicle and having it fall to ground. Because the thermal imaging sensor sits in the nose of the aircraft, it is especially vulnerable during landing, especially a rough one. While it may be unrealistic to expect a sensor to survive a freefall from many meters above ground, the more shock resistant it is, the better the likelihood of withstanding a harsh landing.

Wide field of view. Because of their small size and weight, it is impractical for man-portable UAV systems to include a stabilized gimbal to actively control the sensor line-of-sight. Therefore, a field of view (FOV) that is too narrow is problematic because even the most experienced pilot, flying in calm conditions, will be hard-pressed to maintain angular position of the aircraft relative to a target on the ground. In turbulent conditions or if the operator has limited piloting skills, the probability of maintaining a target within a narrow FOV is low. On the other hand, a FOV that is too wide is also undesirable because spatial resolution is then sacrificed. Low sensor resolution forces the vehicle to fly at low altitude where it is more vulnerable to detection and attack by an enemy, not to mention trees, building, and other obstacles. A sensor with multiple lens options provides the most flexibility for tailoring the FOV to the mission.

High sensitivity / fast frame rate. For many operating scenarios of the miniature UAV, thermal contrast in the scene is low, and high sensitivity is critical to detecting and recognizing targets of interest. Due to the forward motion of the vehicle, scenery is highly dynamic. Therefore, a fast frame rate is required to avoid smearing or jerkiness in the video signal.

4. OMEGA™ AS A UAV PAYLOAD

When Indigo Systems began developing its microsensor product line in 1997, there were no infrared imaging products on the market even remotely suitable for installation in a miniature UAV. Indigo set out to change that situation by designing a camera specifically optimized for very low weight, size, and power consumption. Development activities were funded in part by the U.S. Army under a Dual-Use Science and Technology (DUST) contract, which is a funding vehicle employed by the government to share non-recurring engineering (NRE) costs of a commercial product with substantial military value. An intermediate result of the development effort was the Alpha™ camera, which went into production in 1999 as the world's first miniature thermal imager. It was flown on several platforms and was generally considered a breakthrough product for the miniature UAV industry. However, Indigo was already working to eclipse the Alpha™ with its second microsensor offering. The Omega™ camera, which went into full-scale production in 2002, improved upon every significant aspect of its precursor (see Figure 8 and Table 2). The remainder of this section describes specific design features of Omega that were aimed at product miniaturization.



Figure 8: Alpha™ and Omega, side-by-side

Table 2: Alpha™ and Omega™ comparison

	Alpha	Omega
Weight	186 g (6.5 oz.)	114 g (4.0 oz.)
Volume	175 cm ³ (10.7 in ³)	77 cm ³ (4.7 in ³)
Power	≤2500 mW	≤1500 mW
NEdT f/1.6, 30 Hz	≤ 100 mK	≤ 85 mK
Temp. Range	0 °C to +55 °C (32 °F to +131 °F)	-40 °C to +55 °C (-40 °F to +131 °F)

TEC-less Operation. Historically, uncooled thermal detectors have been incapable of operating without active temperature stabilization of the focal plane array (FPA), usually in the form of a thermoelectric cooler (TEC). One of the main drivers of Omega's improved performance relative to Alpha™ and other thermal imaging products is elimination of the TEC. There are a number of significant drawbacks associated with a TEC, including the obvious disadvantage of added volume (on the order of 5 cm³, not including drive electronics). Power is a major concern, particularly for operation over a wide temperature range. As the difference between ambient temperature and the fixed FPA temperature grows, power consumption of the TEC circuit can exceed that of all other system electronics combined. Changing the FPA set-point during operation (as ambient temperature changes) is not a good option because of the long outage of valid video data during the transition. At turn-on, there is also a delay in valid video as the FPA heats or cools to a stable temperature. For the miniature UAV application, this means vehicle launch is delayed up to a minute while the operator waits to verify that the payload is working properly. Removing the TEC greatly reduces complexity of the camera design, allowing a smaller vacuum package, simpler electronics, and simpler assembly. It also improves operational performance by promoting a wider temperature range, instantaneous turn-on, and vastly improved power management.

The challenge of eliminating a TEC is maintaining uniformity as the FPA heats or cools. Generally speaking, uncooled detectors are highly sensitive to temperature change, and if parameters vary even slightly from pixel to pixel, image quality can degrade radically with temperature. Using a novel combination of proprietary read-out circuitry and non-uniformity correction (NUC) algorithms, Omega™ is one of the first infrared cameras to solve the uniformity problem, maintaining excellent image quality across the full range of operating conditions. Advanced temperature-compensation algorithms minimize variations in pixel behavior over very wide spans of temperature, which means that only three tables of NUC terms are used over the full operating temperature range of the camera, -40 °C to +55 °C. Other TEC-less cameras require many more NUC tables, which negatively affects memory requirements, size, cost, calibration, and system complexity.

Compact Optical Design. Another essential foundation of Omega™ miniaturization is a highly compact optical design. Lenses used in infrared optics are typically made from germanium or other heavy materials, and optical assemblies often represent a substantial percentage of the overall weight of a thermal imager. Reducing lens volume is thus an excellent means of reducing system weight. Decreasing the aperture size (i.e., a slower f/number) is a straightforward approach to smaller lens elements. However, the signal-gathering capability of the optics is directly proportional to aperture area. A detector array with poor inherent sensitivity demands large, heavy optics to compensate for inadequate performance. Conversely, an array with excellent sensitivity supports a compact optical design with slower f/number. The FPA used in the Omega™ camera was designed in-house by Indigo Systems for optimum signal-to-noise ratio (SNR), resulting in < 85 mK noise equivalent delta temperature (NEdT) at f/1.6. By using an f/1.6 design, the cross-section of each Omega™ lens assembly is approximately 60% smaller than comparable f/1.0 optics commonly used with uncooled detectors. Omega™ is offered with three lens options, as shown in Figure 9. These lens assemblies, which are interchangeable in the field, provide a wide 40° x 30° FOV, a medium 25° x 19°, and a narrow 15° x 11°.



Figure 9: Three Omega™ standard lens option.

Another means of reducing the size of the lens assemblies on the Omega™ camera was by simplifying the mechanical design. Thermal imagers use an internal shutter or other uniform surface to periodically update NUC terms. During the update process, the shutter is rotated into the image field, and the pixel response is normalized. On the Alpha™ camera, the shutter assembly was nested in the optical housing, which caused the diameter to grow considerably. On the Omega™ camera, the shutter has been located directly in front of the sensor assembly, as shown in Figure 10, and the resulting mechanical design is much simpler and more compact.

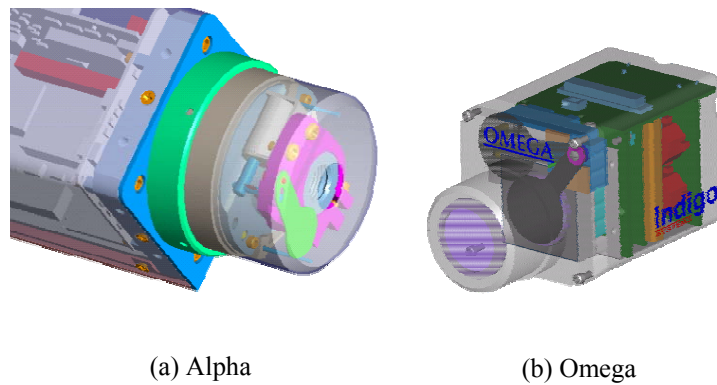


Figure 10: Comparison of shutter packaging on Alpha™ and Omega.

Optimized Electronics Packaging. In addition to compact optics, Omega™ uses novel electronics packaging to shrink camera size. To minimize the cross-section of the camera, circuit cards were sized comparable to the footprint of the sensor package. The result is a multiple-board stack. Interconnecting the stack with standard surface-mount or through-hole connectors would have used a large percentage of the available board real-estate, forcing the stack size to grow. Instead, a single flex-rigid board was employed, as shown in Figure 11. It consists of four 3.0 cm x 3.0 cm (1.2 in. x 1.2 in.) sections, interconnected with an integral flex harness. This board is folded such that all sections are parallel, and the accorded assembly is connected directly to the sensor package. A single motherboard oriented in a perpendicular plane provides the primary I/O connector to the outside world. As illustrated in Figure 12, the result is a dense electronics “cube”.

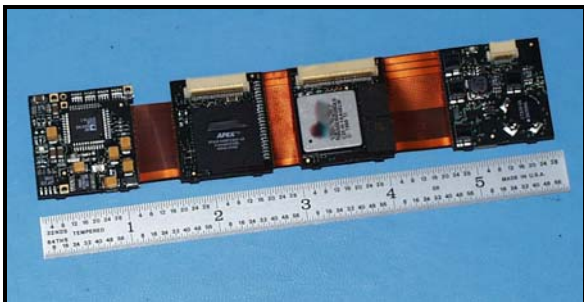


Figure 11: Omega™ electronics unfolded

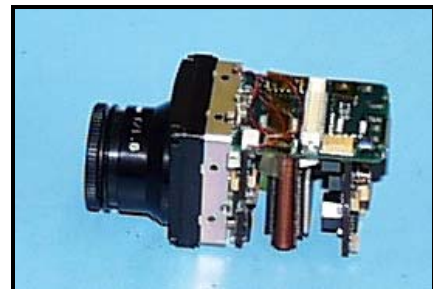


Figure 12: Omega™ electronics folded

5. POTENTIAL SYSTEMS OF THE FUTURE

Smaller even than the previously described miniature UAV systems is another vehicle class referred to as “micro” UAV. With a wing span typically less than 15 cm (6 in), systems such as the AeroVironment Black Widow depicted in Figure 13 represent a tremendous challenge for payload design. Even the tiny Omega™ camera has too much bulk for this application, which requires a payload on the order of 1 to 10 grams (0.04 to 0.4 oz.). Analogous to the situation four years ago when there was a lack of suitable IR payloads for miniature UAVs, today there are no infrared imagers even close to fitting on a micro UAV. Will that situation change in the near future? This section considers some potential design strategies to fuel another quantum leap in size/weight reduction.

Electronics partitioning. In its most reduced form, the data path for most thermal cameras consists of data sampling, non-uniformity correction (NUC) processing, and video processing, as illustrated in Figure 14. Data sampling consists of sensing the thermally-induced electrical change in each detector (e.g., biasing a microbolometer element), multiplexing the signal from every pixel, and digitizing. The result is a data stream with large dynamic range (typically ≥ 14 bits). Because pixel response is generally non-uniform, gain and offset NUC terms are applied on a per-pixel basis. Unless the raw, uncorrected data is extremely non-uniform, the NUC operation does not appreciably lower the overall dynamic range of the signal. Display systems generally have much lower dynamic range (≤ 8 bits), so video processing algorithms map the larger dynamic range to the smaller, typically using nonlinear transforms to optimize the use of the latter. Other video processing algorithms (e.g. polarity reversal) may also be applied but with no additional affect on signal dynamic range.

One approach to reducing system size is to integrate as much processing onto the FPA as possible. On-chip ADC and partial NUC processing are not uncommon on modern FPAs, but video processing algorithms are generally too complex for on-FPA implementation. Another strategy for the UAV application is to partition some of the signal processing to ground-based electronics. This partitioning is likely to increase the bandwidth of the downlink between vehicle and ground station since the signal “upstream” from video processing has higher dynamic range. However, for a small array size or slow frame rate, the higher bandwidth may not be an issue. Therefore, all of the signal processing can either be integrated onto the FPA or relocated to the ground, resulting in a much smaller on-board electronics package. The use of scene-based NUC would further eliminate the need for a shutter assembly, resulting in a very compact payload consisting of the sensor package, a lens assembly, and minimal electronics.



Figure 13: AeroVironment Black Widow Micro UAV

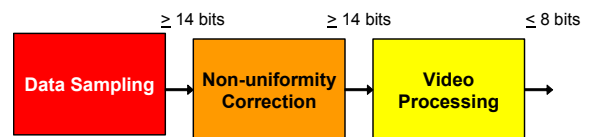


Figure 14: Typical data path in a thermal imager

Alternative Optical Designs. Materials commonly used to make infrared lenses are dense, and thus optical assemblies are typically heavy. As previously described, a well-known trade to reduce lens size is to increase f/number. However, even the compact f/1.6 lens assembly used on Omega™ weighs approximately 30 g (1.1 oz), several times heavier than the weight budget for the entire payload on a micro UAV. A slower optical design is unlikely to produce the dramatic weight reduction required for this application. Other potential avenues for lightweight optical assemblies are employing diffractive elements and/or alternative materials. Diffractive elements essentially eliminate much of the bulk material from the design of a lens element while retaining its light-bending properties. The technology is currently transitioning into the mainstream within the infrared industry and offers real potential for lightweight optics. The use of alternative materials (e.g., molded plastics) is a less mature technology path but still offers the potential for a breakthrough.

Smaller FPAs. While the FPA generally represents a small fraction of the overall size and weight of a thermal imaging system, reducing active area has a proportional affect on the size of optical assemblies. The two variables affecting active area are pixel size and number of pixels. Currently, 25 micron pixels represent the smallest common pixel size, and state-of-the-art FPA designs are pushing the envelope below 20 microns. Reducing array format (e.g., 80 x 60) clearly reduces FOV and/or resolution of the imager, but this concern is mitigated by the fact that a micro UAV is inherently more stealthy than larger vehicles. It can fly closer to the target undetected, which means the number of pixels on target might remain constant (or even increase) despite a reduction in the number of pixels on the FPA.

6. SUMMARY

Man-portable UAV systems provide tremendous opportunity to the military and law-enforcement community. They can be deployed rapidly with little or no site preparation, with minimal training, without exposing the crew to hostile situations. And they are stealthy, rugged, and low-cost. By providing imaging capability in absolute darkness and low-visibility conditions, the Omega™ camera further extends the utility of miniature UAVs. As summarized in Table 3, the Omega™ camera is extremely well-suited as an infrared imaging payload for miniature UAV systems. The next hurdle for the infrared community is further sensor miniaturization to provide thermal sensing capability to micro UAVs that demand a payload less than 10 g.

Table 3. Omega’s capabilities as a miniature UAV payload.

Requirement for a Miniature UAV payload	Omega™ Performance
Small	< 77 cm ³ (4.7 in ³), including lens
Lightweight	< 114 g (4.0 oz.)
Low power consumption	< 1.5 W
Rugged	<ul style="list-style-type: none"> • Qualified against extreme shock / vibration • Wide operating temperature range
Easily integrated	<ul style="list-style-type: none"> • Power-in / video-out operation (fully automatic) • Wide input voltage range (runs directly off vehicle battery) • Standard NTSC output channel
High sensitivity	<ul style="list-style-type: none"> • < 85 mK at f/1.6 (equivalent to 33 mK at f/1.0) • 30 Hz frame rate
Sufficient FOV / range	Three lens options. FOV and resolution can be optimized for the mission.