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White Paper

From Scanning to Seeing: How Hyperlux™ ID Empowers the Next Generation of Machine Vision

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From Scanning to Seeing: How Hyperlux ID Empowers the Next Generation of Machine Vision

Depth perception is the critical piece of functionality that real-world machine vision applications rely on. Hyperlux ID Indirect Time of Flight depth sensors from **onsemi** make precise depth perception practical using fewer, smaller, simpler components.

Figure 1.

Modern machines don't just move. They must navigate their surroundings, recognize the objects that they are handling, and interpret the world around them. True automation for industrial components depends on their ability to perceive, locate, and interact with the world. When these components are driven by AI, they'll need depth sensors capable of giving their processors a sense of visual awareness.

This level of recognition — *awareness* — is a tricky thing to achieve for machine vision.

When a machine manipulates objects or is navigating the space in front of it, its processor needs to acquire as many *depth points* as it can, in as short an interval of time as possible. A conventional image sensor encodes a plethora of digital artifacts, including blooming, smearing, oversaturation, and motion blur. None of these things are *things*, but without depth sensing and a way to interpret its data meaningfully, a machine's processor won't be able to make that inference. We could hope AI or some machine learning algorithm might help it distinguish between reality and illusion. But what's truly necessary here is a depth sensor powerful and reliable enough to render the need for divining the truth from unreliable visual evidence unnecessary.

This white paper is about matching the right depth sensor device to the application at hand. As one of the world's principal manufacturers of semiconductor components, **onsemi** makes sensor devices, including CMOS-based image sensors, ultrasonic, and short-wave infrared (SWIR) sensors, as well as LiDAR.

What makes LiDAR effective in sensing depth at long distances is its use of *direct time-of-flight* (dToF), as explained in this white paper [PDF]. When the most important element of data for an application at any one time is how far away things are, dToF provides LiDAR with faster acquisition rates than any other depth sensing method, as well as the ability to detect multiple objects within the laser's return path. Using two-dimensional single photon avalanche diodes (SPAD) and silicon photomultiplier arrays (SiPM), **onsemi** LiDAR components are capable of detecting single photons at a range of up to 300 meters.

What's lacking in LiDAR is resolution. To cover a full field of view, LiDAR has to scan the scene in front of it, like a brush washing paint over the full area of a canvas. With this method, it's difficult to detect the identity of an object in the distance, especially without the clearest sense of where its edges are.

The engineers of tomorrow's machine vision applications need to understand the difference, and choose the right imaging device for the work they're developing.

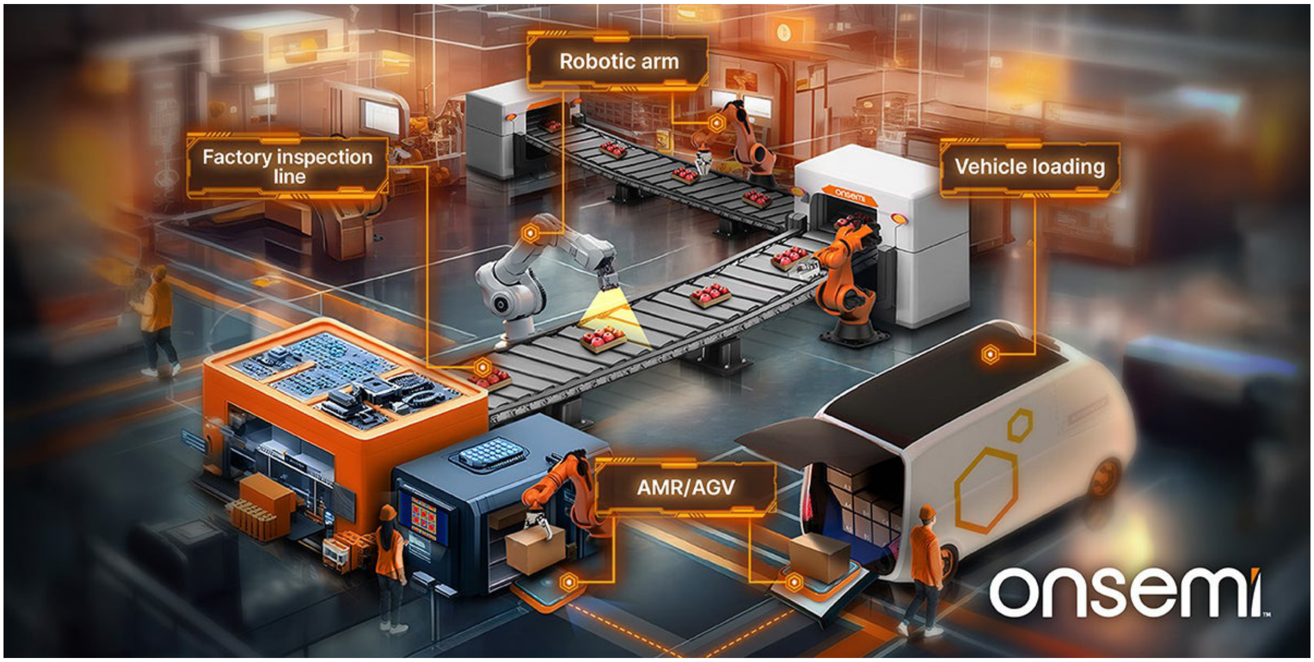


Figure 2.

When machine vision system records the presence of an object just within its reach, it needs to infer not just its distance but its shape and form. It needs more data about the scene in front of it, using points that are more densely packed together for greater resolution and fidelity. For example:

- **Industrial security systems** train their focus upon a gate or particular point of ingress, detecting movement or activity within a roughly 10-meter radius
- **Videoconferencing systems** photograph people within frame who may at times get up and walk around the room, triggering adjustments in position and focus
- **Inventory management systems** in warehouses and fulfillment centers are continually verifying available supplies of goods, along with their storage locations
- **Factory inspection systems** continually examine parts and components for potential faults and defects
- **Logistics systems** frequently measure and dimension goods and packages, so that their shipping methods may be optimized and made safer
- **Vehicle loading systems** continually transfer purchased goods from inventory shelves to shipping vehicles

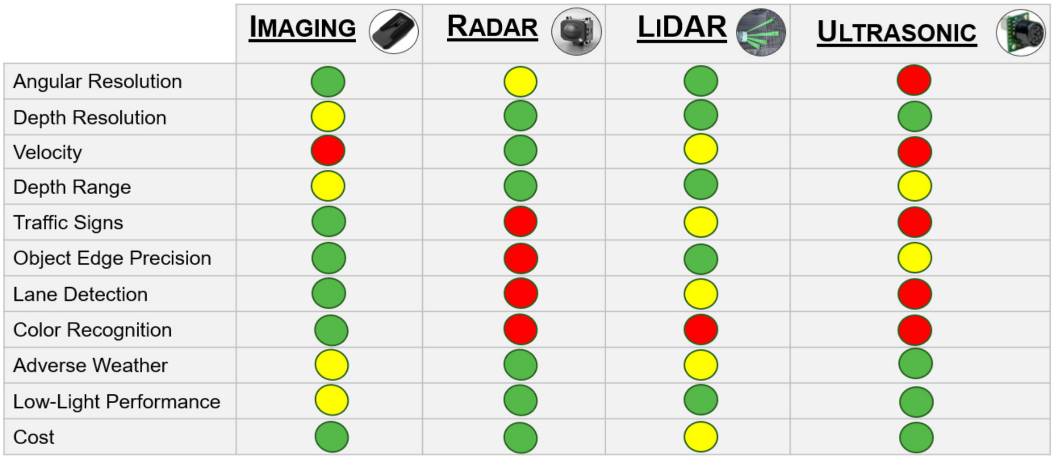
Applications such as these require *high-resolution depth sensors* identify the objects in front of them, and to help software infer the best way to gather, move, or manipulate them. Inferring the identity of an object from its shape or form requires depth perception. That's complicated, because images are still two-dimensional. But there are methods for inferring three-dimensional information from two-dimensional data. The latest of those methods are built into **onsemi**'s latest Hyperlux ID iToF depth sensors.

Learn More from onsemi

- LiDAR components for long-distance range-finding, including for automotive and logistics
- Advanced stereo 3D sensing for autonomous vehicles
- Ultrasonic sensors for guiding autonomous and driver-assistance vehicles through obstacles, including parking
- Hyperlux CMOS-based image sensors for a wide range of industrial applications, offering high dynamic range and optimal low-light performance

The Depth Perception Problem

Distance is a one-dimensional concept. A laser beam perfectly embodies both the benefits and the limitations of what can be perceived in one dimension of space. For a device whose sensory mechanism is the laser beam itself, determining the composition of the environment in front of the sensor is a matter of making multiple scans and assimilating the data from those scans. Technological progress is speeding up this scanning process, though there continue to be physical limits.



	IMAGING	RADAR	LiDAR	ULTRASONIC
Angular Resolution	🟢	🟡	🟢	🔴
Depth Resolution	🟡	🟢	🟢	🟢
Velocity	🔴	🟢	🟡	🔴
Depth Range	🟡	🟢	🟢	🟡
Traffic Signs	🟢	🔴	🟡	🔴
Object Edge Precision	🟢	🔴	🟢	🟡
Lane Detection	🟢	🔴	🟡	🔴
Color Recognition	🟢	🔴	🔴	🔴
Adverse Weather	🟡	🟢	🟡	🟢
Low-Light Performance	🟡	🟢	🟢	🟢
Cost	🟢	🟢	🟡	🟢

Figure 3. The Capabilities Inherent to Four Prominent Visual Technologies. Green: Commonly Used; Yellow: Occasionally Used but not Always Reliably; Red: Never Used.

Depth perception requires at least one two-dimensional image, although with two or more it's possible to infer three-dimensional information. The effective range of an image sensor equipped with depth perception is limited by the sensor's resolution. This is a limitation a laser beam doesn't have. You can equip a low-Earth orbit (LEO) satellite with a LiDAR and make very precise maps of surface and ocean levels from a thousand miles' altitude.

It's this distinction that defines the realms of practicality for LiDAR and image sensors in industrial applications. Today, more automated tools in everyday environments are utilizing CMOS-based image sensor technology for use in depth sensing. For consumer-grade digital cameras, CMOS-based sensors used to be impractical, especially for professional photography. They were sensitive to optical noise and electromagnetic interference, for which the first charge-coupled devices (CCD) in digital cameras could very effectively compensate.

The smartphone era changed all that, by leveraging technology created by NASA's Jet Propulsion Laboratory for the space program, to optimize the efficiency and practicality of CMOS. Today, **onsemi**'s CMOS-based Hyperlux ID AF0130 and AF0131 offer many benefits over both CCD-based image sensors and LiDAR components, including:

- **Greater power efficiency** for applications requiring low DC voltage or battery power

- **Easier integration** into machine designs and component packaging
- **Greatly improved thermal characteristics**, eliminating the need for active cooling. By comparison, LiDAR's photodetectors are particularly sensitive to heat, especially at temperatures at or above 35 °C.
- **Highly accurate depth perception**, leveraging 1.2 megapixel (MP) resolution with back-side illumination (BSI), along with image processing power embedded on the sensor itself to greatly improve accuracy
- **Faster image exposure** with techniques that optimize the way the sensor processes, stores, and reads out images
- **Greater programmability**, including through the use of contexts to fine-tune image sensors to best fit the applications that rely on them

LiDAR and Direct Time-of-flight

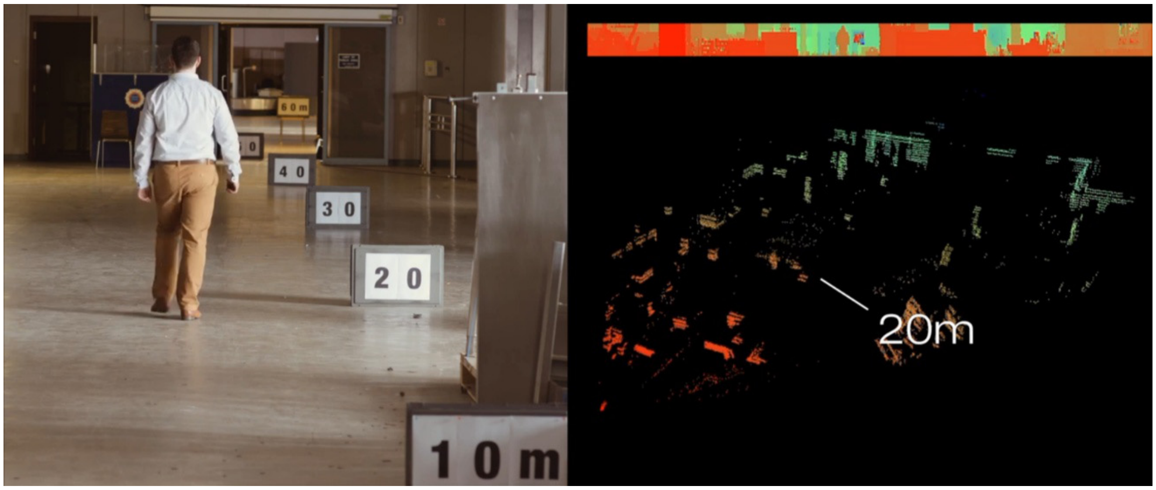


Figure 4. Footage from a Demonstration of LiDAR Sensing Technology. Just to the Left of the "20 m" Callout at Right is an Orange Reflection Coming from the Walking Man. As he Proceeds Towards the "4.0" Milestone, his Reflection will Proceed Toward the Upper Right of the Graph and Turn Green to Denote Greater Distance.

As you may know, LiDAR applies the radar principle to light waves. It measures depth and distance between a laser and the object to which it's pointed, by assessing the waveforms of light reflected from that object. In geological and satellite-based applications, LiDAR often relies upon GPS for accurate positioning. Much like the way sonar listens for returning sound waves to judge distances between their emitter and the object echoing them, the LiDAR approach applies laser pulses to the radar principle.

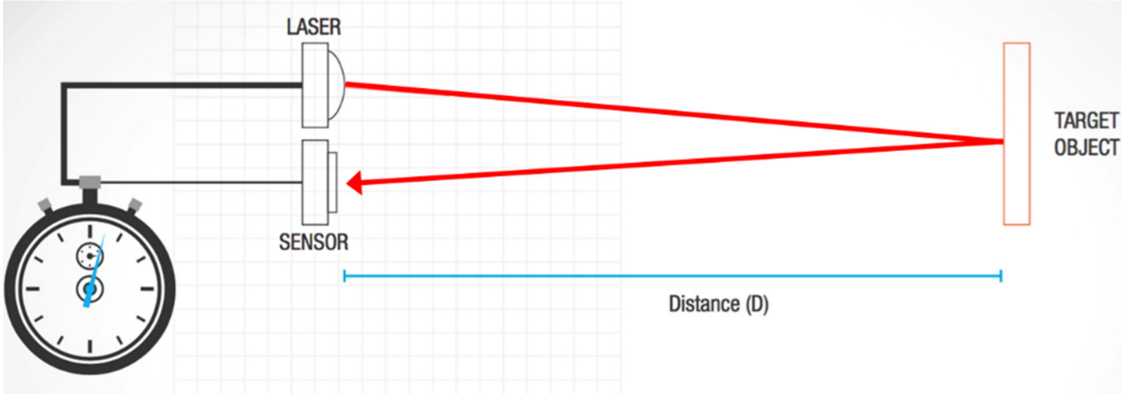


Figure 5.

As LiDAR components go, a solid-state SiPM uses the least power, while retaining a very high resistance to electromagnetic and optical noise. An unauthorized moving figure 60 meters away generating only about 10% reflectivity may be easily spotted, affording plenty of time for security systems to kick in, ingress points to be secured, and alerts to be issued.

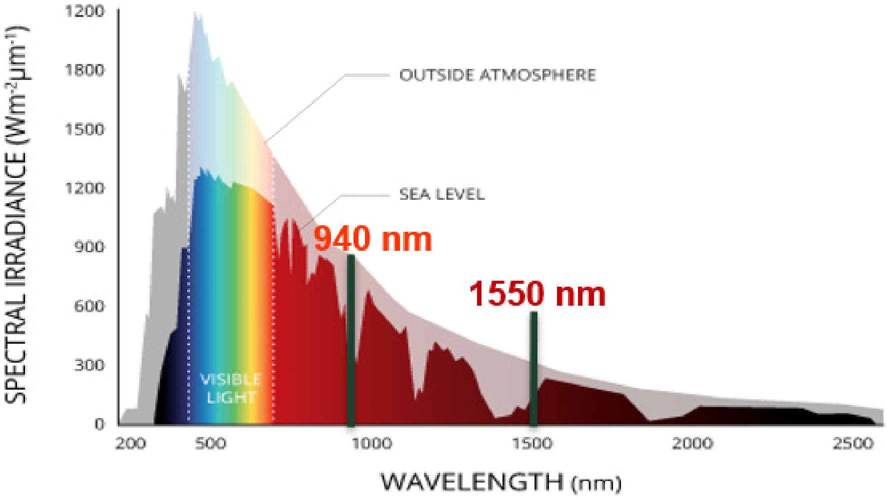


Figure 6. From Standard Tables for Reference Solar Spectral Irradiances (ASTM International)

The graph above represents the relative quantities of photons detected both inside (darker) and outside (lighter) the Earth’s atmosphere, projected by the Sun. As wavelengths increase, note the cavern-like dips in photon levels at 905 nm and 940 nm in the near-infrared (NIR) portion of the spectrum, and 1550 nm in the shortwave infrared (SWIR) portion. Ambient light from the Sun contains much fewer of these wavelengths, making them into prime real estate for use in LiDAR. A majority of **onsemi** customers are working with applications in the 905–940 nm band, which is also where customers will find the most cost-effective LiDAR components.

Single-point depth perception capability is practical and efficient when the application at hand is to infer from light waves whether or not there’s *something* in the distance in the direction of the laser beam. A meteorologist or a geologist might be interested in the spectrographic analysis capabilities made feasible by the returning LiDAR wave. But for everyday industrial purposes, when the focus of the application is a binary state — the presence or absence of something ahead — an SiPM is the perfect choice as a light sensing component.

Learn More from onsemi

- How LiDAR can be used for Industrial Range Finding
- SiPM dToF LiDAR Platform Getting Started Guide [PDF]
- Video: Gen3 SiPM LiDAR Demonstrator System Indoor Testing
- Video: High Resolution Shortwave Infrared (SWIR) Imaging

Hyperlux ID and Indirect Time-of-flight

Figure 7.

CMOS-based image sensors have a limited range of depth perception. Under normal conditions, a CMOS sensor's *unambiguous range* would have a hard stop at one cycle of light modulation. The location of that hard stop $\mathbf{D_{max}}$ is calculated using this formula:

$$D_{max} = \frac{c}{2f_m} \qquad \text{(eq. 1)}$$

where the constant **c** represents the speed of light, and $\mathbf{f_m}$ represents the modulated light frequency. For example, a sensor modulating at a single frequency of 60 MHz would have an unambiguous range maximum limit of only 2.5 meters.

Hyperlux ID is designed for deployment in settings such as factory floors and packaging conveyors. Here, robotic systems require precise measurements of distances between the surfaces of manipulators and delicate materials such as food.

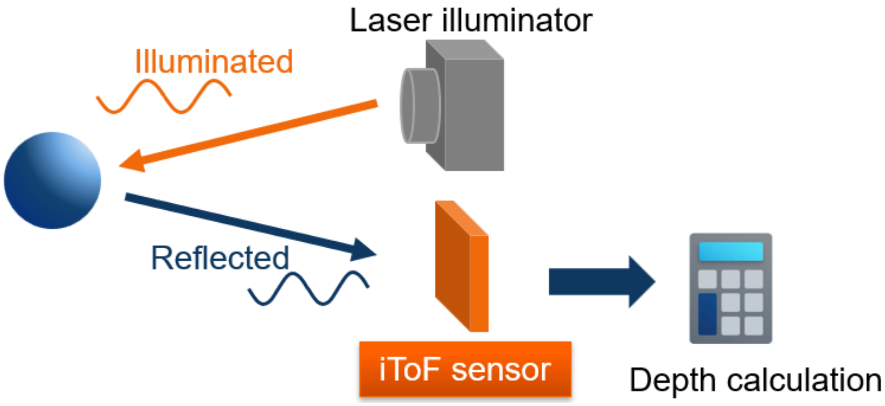


Figure 8.

In these environments, it becomes easier and more practical to measure depth using *indirect time-of-flight* (iToF). Like LiDAR, iToF does compare reflected light to emitted light, though by way of inferred information. Using a 940 nm infrared laser diode as an illuminator, Hyperlux ID captures all the received light, all at once, through its *global shutter*. By comparison, a rolling shutter exposes the sensor to light top-to-bottom, like an old mechanical barrel shutter. This may be satisfactory for consumer-grade digital cameras, although even iToF methods would not fully compensate for a rolling shutter's deficiencies.

Hyperlux ID's global shutter enables it to capture eight simultaneous exposures (four phases at two frequencies each), and then store the data from those exposures together as a single captured frame. This reduces motion-induced phase errors to the point of near-elimination.

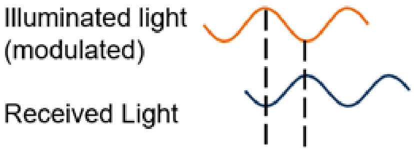


Figure 9.

When light from a constant modulating source such as a laser is reflected by an object, the echoed light will be slightly out of phase. The degree to which it's out of phase informs the sensor as to distance, although it takes some math to deduce what that distance is. The phase shift between the received light wave and the modulated wave is calculated by assessing the wave amplitude at the edges of the four quadrants: 0°, 90°, 180°, and 270°. The phase difference $\Delta\Phi$ is calculated using the two-argument arctangent formula:

$$\Delta\Phi = \mathrm{atan2}(I_{90} - I_{270}, I_0 - I_{180}) \qquad \text{(eq. 2)}$$

With the phase difference **$\Delta\Phi$**, the modulation of the laser frequency **f_m**, and the speed of light **c** all known values, solving for distance **d** at each point becomes academic:

$$d = \frac{c\Delta\Phi}{4\pi f_m} \quad \text{(eq. 3)}$$

This is how indirect time-of-flight infers distance data from image data that contains phase shifts. It lends itself to depth perception applications because the phase data is effectively captured in parallel through the global shutter, rather than serially through a moving laser. However, with a single modulator, iToF is only effective at very short ranges. **onsemi** overcomes these limitations somewhat through a very clever, patented methodology called **Smart iToF**.

Learn More from onsemi

- How High-Speed Global Shutter Image Sensors Ease the Burden on AI-based Vision Systems
- Overcoming Existing Challenges of Indirect Time-of-Flight with Technology Advancements
- Video: Choosing the Right Image Sensor for the Right Application

How Hyperlux ID with Smart iToF Overcomes Real-world Challenges

Hyperlux ID is an image sensor that leverages iToF to perceive depth information — making it a depth sensor. Coupled with an active illumination system such as a Vertical Cavity Surface Emitting Laser (VCSEL), Hyperlux ID calculates phase shifts of the returning light from both the VCSEL's laser and its own, modulating both their intensities in the process. By alternating between two different frequencies in one exposure time, the sensor's maximum unambiguous range **D_{max}** is extended using a lower denominator: specifically, the greatest common devisor **GCD** of the two frequencies:

$$D_{max} = \frac{c}{2 \cdot GCD(f_1,\ f_2)} \quad \text{(eq. 4)}$$

30m, indoors

70% reflective target

Depth Map

20m outdoors, ~20KLux

70% reflective target

Depth Map

Figure 10.

In tests involving **onsemi**’s evaluation kit, AF0130 was able to clearly record 70% reflective target at 30 meters under fluorescent light in a light, neutral-colored hallway, and at 20 meters in the shade on a hazy day under 20,000 lux of illumination. In the false-color depth maps shown above, the recorded color corresponds to the approximate distance of the reflecting object.

Calculating Depth More Perceptively

AF0130 contains an embedded depth-processing ASIC that handles all its depth perception arithmetic on-board. For customers who prefer to use their own depth processing algorithms, **onsemi** offers the AF0131Real-time processing enables depth data to be put to use immediately for functions such as robot positioning and maneuvering, collision avoidance, physical security alerts, and human gesture detection.

For Smart iToF to calculate depth more accurately, it estimates the *reflectivity* of each pixel in four separately captured frames — one for each 90-degree phase of the waveform. Utilizing this reflectivity data, AF0130 can produce a *depth map*, combining the data from all four frames into a single frame.

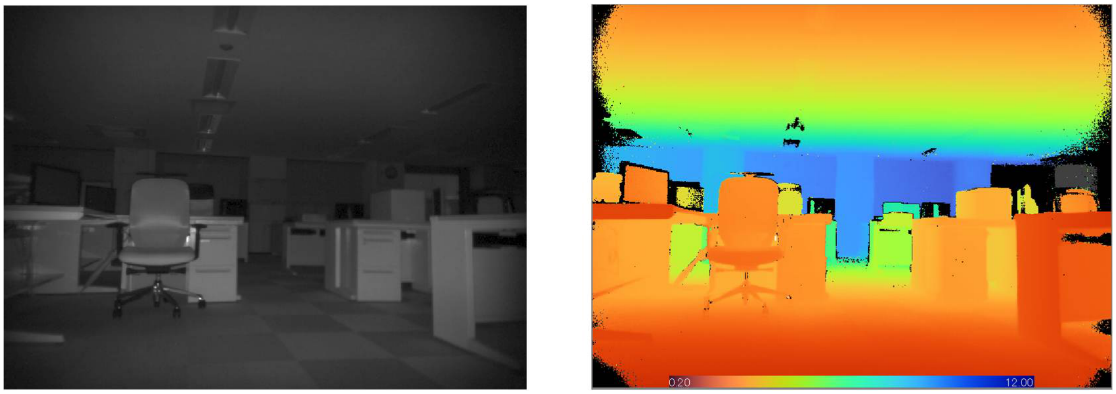


Figure 11. Left: Single-frame Monochromatic Test Image. Right: Depth Map between 0.2 and 12.0 Meters, Compiled from Four Simultaneously Captured Images.

For each given point in the depth map, *pixel response* is a function of the reflectivity of the subject at each given point, calculated as $\mathbf{R_{pix}}$ using this formula:

$$R_{pix} = f(\rho D + A) \qquad \text{(eq. 5)}$$

where ϱ represents the reflectivity of a pixel, **D** the distance between the image sensor and that pixel, and **A** the level of ambient light impacting that point. The reflectivity of an object is another way of expressing the strength of the light signal produced by that object. Visualization software enables relative depth to be represented chromatically — nearer objects in the redder portion of the spectrum, further objects on the opposite end toward blue-violet.

Sensing Depth More Accurately in High Ambient Light

An abundance of ambient light can oversaturate the depth signal received from any pixel to the point of obliteration, making it the enemy of iToF depth sensing. Whenever the scene in front of the sensor is flooded with light (think of an industrial assembly shop floor) it becomes more difficult for any image sensor, but especially a CMOS-based sensor using iToF, to determine depth and distance.

Mitigating the effects of ambient light requires an image processing technique of *ambient light rejection*, overcoming the effects of oversaturated surfaces through clever use of optical principles and wavelength modulation, treating optics as though it were acoustics. An over-abundance of ambient light creates challenges in measuring distance and reflectivity. Hyperlux ID overcomes these challenges by optimizing illumination power (within reasonable eye safety limits) along with integration time, tuning the amount of integrated light over a given measurement period to be tuned to greater or lesser amounts.

Eliminating Motion Artifacts

The next challenge for a CMOS-based image sensor using iToF is to eliminate *motion artifacts*, which are the surreal or unrealistic elements of an image attempting to capture objects in motion. With an ordinary CCD-based digital camera, an object in motion at speed shows up in an image as a blur. Since a similar-looking blur would show up in a film camera image, it can be overlooked as a fact of photography or even an artistic embellishment.

For a high-speed photodetector, what might normally show up as a blur — for example, spinning propeller blades, or a robotic armature in fast motion on the opposite side of the conveyor belt — may appear instead as a strange, disembodied thing hanging in space. It's not a thing, so it's up to the image processing element not to treat it as a thing.

AF0130's artifact compensation process begins with its global shutter, which exposes each pixel to incoming light simultaneously.

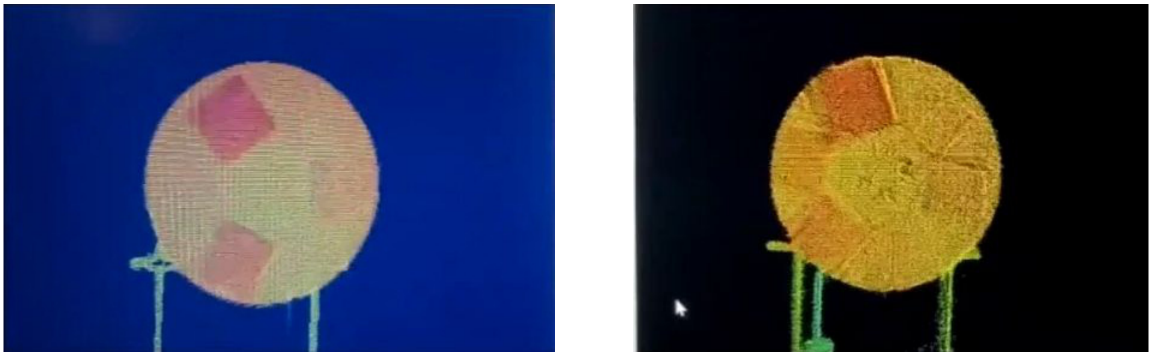


Figure 12. Left: onsemi AF0130 with Smart iToF. Right: Competitor's iToF Sensor.

To test the efficacy of this Smart iToF method, **onsemi** conducted a test using a simple spinning wheel with three blocks of wood attached, each with a different thickness (darker blocks are thicker). The competitor's sensor consistently recorded frames where the wheel appeared to have six blocks attached — an optical illusion caused by the way its sensor interacted with light, including ambient light. By comparison, the video captured with AF0130 recorded a different optical illusion, where each frame contained only three blocks, but their positions would appear to shift only slightly and then trade places with each other for a blinking effect. Each frame captured by AF0130 was more true to reality, and the depth map generated using collections of these frames is far more accurate.

The way a typical frame exposure is handled by an imaging system, the exposure data is written to memory, then time is allotted for the *readout phase*. This is the period when pixel values collected from the sensor are digitized in sequence and committed to memory. Ordinary image sensors are programmed to expose the sensor and immediately begin the readout phase. If a sensor needed to perform that method eight times for eight frames in succession, the time gap between exposures would be too great for the components of the depth map to match one another. The results would be more likely to include a greater number of motion artifacts, which for a real-world setting like a busy city street or an assembly line conveyor belt, would be unacceptable.

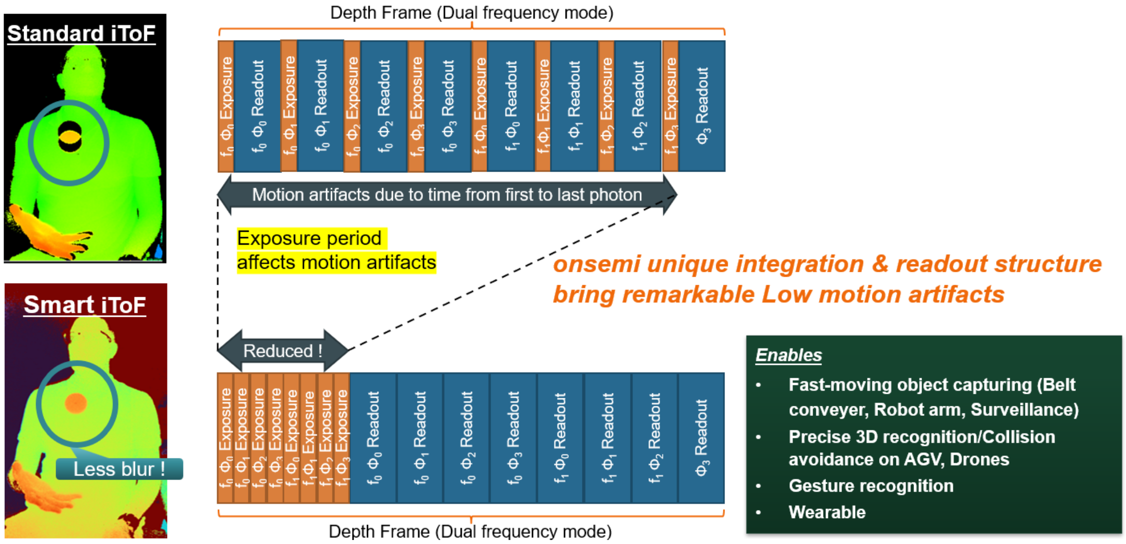
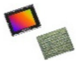


Figure 13.

AF0130’s Smart iToF overcomes this challenge by exposing all eight frames together in sequence first, and then delaying the readout phases for each frame until all eight frames have been exposed. This results in greatly reduced blur, which increases the reliability of gesture recognition systems that need to distinguish informational arm motions from blurs. (Minor time gaps do remain between exposure periods, though small enough to become trivial.)

Here’s the math for a typical AF0130 exposure scenario: Standard image recording speed for a 1.2 MP sensor is about 29.97 frames per second. With a throughput rate for the MIPI storage bus of 1.2 Gbps per MIPI lane, an optimum exposure time (the *first-to-last photon* speed) would be 300 μs. Each pixel in a stored frame is 12 bits, so with two MIPI lines active simultaneously, throughput speed should be about 200 megapixels per second (MP/s).

Table 1.

	onsemi **AF013x** **ODCSSP87 Package** 	
Optical Format	1 / 3.2 inch (5.60 mm)	
Aspect Ratio	4:3	
Active Pixels	1280 h x 960 v	
Pixel Size	3.5 x 3.5 μm Back-side illuminated (BSI)	
Shutter Type	Global shutter	
One-Time Programmable Memory (OTPM)	3 x (1024 x 24 bits)	
Input Clock Range	10–30 MHz	
ADC Resolution	10–11 bit	
Analog Gain Range	1–7.75x gain	
Maximum Frame Rate Mode 2.2	60 fps 1.2 MP	0 fps VGA
Maximum Frame Rate Mode 3.2	N/A	54 fps VGA
Operating Temperature T_J	$-30\ °C < T_J < +85\ °C$	
Junction-to-air Thermal Resistance $R_{\theta JA}$	32 °C/W	

A 1.2 MP image contains 1280 x 960 pixels, so the readout phase for that image would consume 6.1 ms. Hyperlux AF0130 can store all the exposure information in the sensor prior to the first readout phase beginning. By comparison, a competitor's sensor would interleave three readout phases between the first four frames. That means its first-to-last photon speed would be 0.3 ms x 4 + 6.1 ms x 3 = **19.2 ms**.

Compare this figure against AF0130, whose first-to-last photon speed would be 0.3 ms x 4 + 0.25 ms x 3 = **2 ms**. This simple process gives AF0130 **9.6x** better motion performance at 29.97 fps.

In another scenario, suppose the frame rate is stepped up to about 60 fps. Each MIPI lane would require 2 Gbps for proper throughput to enable depth processing, but let's assume that's feasible. At that throughput rate, which is effectively 333 million pixels per second, the readout rate for one frame would be 3.7 ms. AF0130's first-to-last photon speed would be 0.1 ms x 4 + 0.25 ms x 3 = **1.15 ms**. Compare that to a competitor with 0.1 ms × 4 + 3.7 ms × 3 = **11.5 ms**. This gives **onsemi**'s Hyperlux ID-class sensor even faster motion performance: **10x** the competitor at 60 fps.

Enabling Adaptability and Fine-tuning with Contexts

Calibrating Hyperlux ID's global shutter enables the image sensor to be fine-tuned for specific applications. For example, for a situation where the sensor is tuned to a conveyor just two meters away, AF013x can be calibrated to concentrate on reflected light from less than four meters. Specifications that fine-tune the operating characteristics of a sensor can be stored in the sensor itself, as *contexts*. This way, contexts may be swapped out for one another as the application at hand changes.

AF013x is capable of making some adjustments dynamically as well. For example, when a reflecting object gets very close and the exposed light intensity becomes too high to make out much detail, AF013x can be set to automatically decrease its exposure time. Alternately, if the global shutter is set for further distances and a near object comes into frame, *dynamic context switching* enables the sensor to reset itself immediately, so that the near object isn't just a massive blur. This is useful, for instance, in a surveillance system where the sensor is normally tuned for a gate 10 meters away, but a moving object — even a fast one — comes into frame at 2 meters.

Reducing System Complexity and Cost

For a standard, single-modulator image sensor using iToF, the algorithms for calculating depth perception are typically handled by a separate microcontroller or FPGA array. Hyperlux ID AF0130 integrates these functions directly onto the chip. Suddenly, your component design no longer requires these separate parts:

- **An off-chip microcontroller or FPGA array**, which would need its own power tree and voltage rail
- **Frame memory units**, which often require memory controllers
- **A high-speed interface linking the image sensor**, the microcontroller, and the memory

Integrating depth processing into the image sensor reduces bandwidth, lessens compute requirements, simplifies the design of the component that incorporates the image sensor, minimizes that component's size, and lowers its manufacturing and operations costs.

Learn More from onsemi

- AGB1NOCS-GEVK evaluation board for AF0130 and AF0131
- Video: Advancements with Indirect Time-of-Flight

Quantifiable Results from Hyperlux ID

onsemi's Hyperlux ID AF0130 and AF0131 depth sensors deliver results that can transform the design of industrial components using machine vision, making them easier to build, easier to maintain, simpler to engineer and develop, and easier to afford.

- **AF013x's 1.2 MP BSI global shutter mechanism** enables the most accurate depth perception capability possible from a CMOS image sensor
- **Smart iToF with on-chip storage** reduces, or even eliminates, motion artifacts, increasing the accuracy of AI software that requires accurate machine vision for image and object recognition systems
- **Integrated on-chip algorithmic processing** completely eliminates the need for external microcontrollers, which in turn simplifies and shrinks component design while reducing power requirements
- **Maximized ambient light rejection** improves unambiguous range, enabling a wider array of new machine vision applications
- **Open software development and programmability** with customizable contexts using **onsemi**'s industry standard Devware X environment

The Bigger Picture: Toward True Machine Vision

Hyperlux ID solves the issue of making machine vision practical and adaptable, in situations and environments where speed and accuracy cannot be sacrificed, but very long-range perception is not a requirement. Modern machines need to see what they're doing. They need only the depth and positioning data that is relevant to what's happening in that critical microsecond. There was a time when low-power CMOS technology, with its susceptibility to heat and noise, would have been the wrong option for these applications. But that time is now long past, as improved engineering and clever programming have enabled CMOS not only to overcome those deficiencies, but to outperform older technologies like CCD.

As machine vision becomes a ubiquitous function of any device that deals with space and time, industrial mechanisms need image sensors whose technology, reliability, supply chain, and support systems make them worthy of ubiquity. **onsemi** delivers components that uncomplicate the machine vision ecosystem.

REVISION HISTORY

Revision	Description of Changes	Date
0	Initial document release.	1/14/2026
1	Chinese version added.	3/19/2026

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