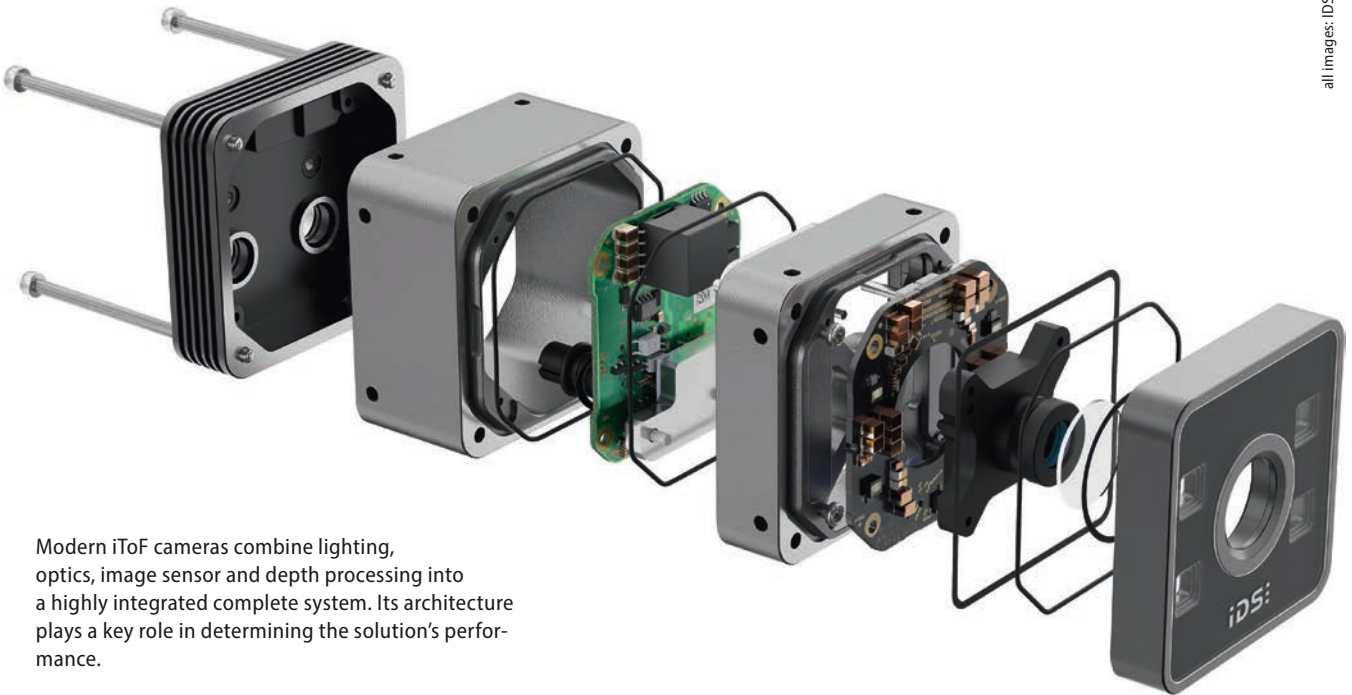




Modern iToF cameras combine lighting, optics, image sensor and depth processing into a highly integrated complete system. Its architecture plays a key role in determining the solution's performance.

The many faces of time-of-flight

The measurement principle alone reveals little about the performance of a ToF system.

Heiko Seitz

Time-of-flight primarily describes distance measurement based on the time it takes for light to travel. However, the actual performance of a system depends on its technical implementation. A look at dToF and iToF shows why the measurement principle alone says little about the properties of a ToF system.

Time-of-flight (ToF) is today considered one of the most important technologies for capturing three-dimensional image data. In robotics, logistics, quality assurance and industrial automation, ToF systems enable the direct acquisition of distances and depth images in real time. At the same time, the term “ToF” appears in a wide variety of technological contexts, ranging from SPAD cameras and dToF sen-

sors to industrial iToF cameras and LiDAR systems. From a technical perspective, however, many of these systems have far less in common than the shared term might initially suggest.

This is precisely where a common cause for misunderstanding lies. ToF initially describes just the principle of distance measurement via the time-of-flight of light. However, the specific characteristics a system subsequently possesses depend largely on its technical implementation. This becomes particularly clear when considering the examples of direct Time-of-Flight (dToF) and indirect Time-of-Flight (iToF). A closer look behind the umbrella term “ToF” reveals that the measurement principle alone says very little about the characteristics of the resulting system.

Two principles, many systems

Terms like dToF and iToF are often used interchangeably with specific cameras or even complete 3D systems. In fact, however, they initially simply describe two different methods of measuring the time taken for light to travel and using this to determine a distance.

It is important to note that neither dToF nor iToF are necessarily 3D technologies in themselves. Both methods initially simply describe how distance or depth information is derived from the time-of-flight. The same measurement methods can therefore be used in a wide variety of applications – from one-dimensional distance sensors and scanning LiDAR systems to 3D cameras capable of capturing large areas. The common practice

of equating dToF or iToF with a specific class of camera is therefore too simplistic.

Only by combining suitable light sources, receivers and assessment methods can specialized systems for distance, depth or 3D sensing be created. The key difference lies in the type of measurement. While dToF determines the actual transit time of a transmitted light pulse, iToF calculates the distance based on the phase shift of a modulated light signal. Both methods are therefore based on the same physical principle, but place different demands on sensor technology, lighting and signal processing. This results not only in different technical characteristics, but also in different system costs. The direct measurement of individual light transit times requires an extremely precise time base and correspondingly specialized sensor and evaluation electronics. iToF systems, on the other hand, utilize phase measurement of modulated light and benefit from the high integration density of modern CMOS technologies. This makes it possi-

ble to produce high-resolution yet cost-effective 3D cameras.

This reveals initial differences in terms of range, resolution and cost-effectiveness. However, a system's actual capabilities are determined by its specific technical design. A closer look at the individual components of a ToF system shows why this system-level perspective is crucial.

Architecture follows function

The final technology decision is not made at the level of dToF or iToF, but rather in the technical design of the complete system architecture. It is only through this process that the characteristics of a ToF system are determined.

Every ToF system consists of a transmitter, a receiver and a processing unit for calculating distance or depth information. The choice of these components is closely interlinked, as they must be coordinated with one another.

As a result, even systems using the same ToF method can differ significantly in their character-

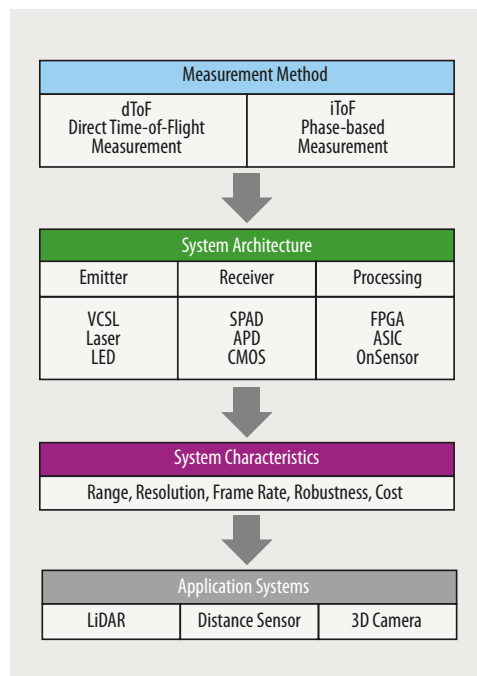
istics. Anyone discussing ToF should therefore not ask about dToF or iToF, but rather about the transmitter, receiver and processing unit.

Different levels of a system

Terms such as SPAD, APD, CMOS and LiDAR are often mentioned in the same breath as dToF and iToF, but they describe different levels of a ToF system. Whilst dToF and iToF describe the measurement method, SPAD, APD and CMOS refer to receiver technologies.

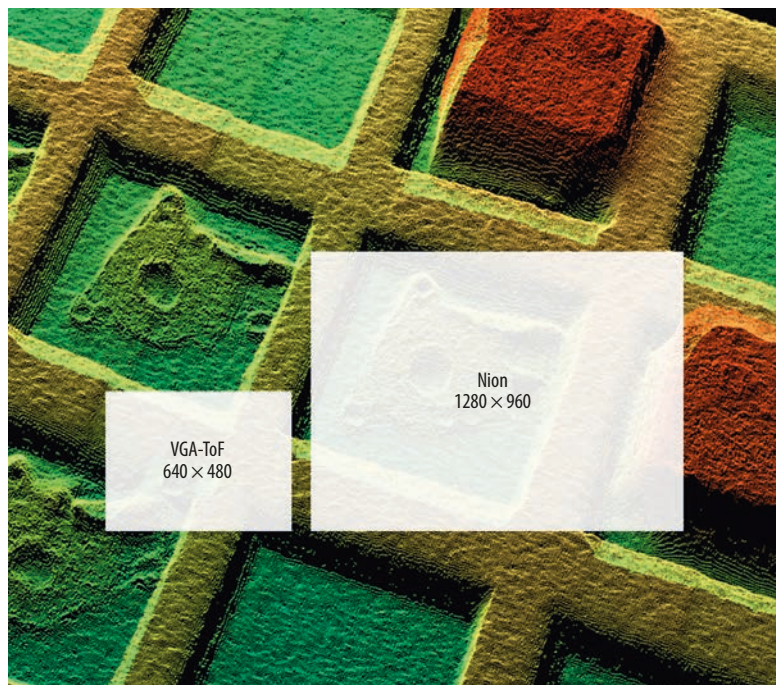
SPAD sensors can detect individual photons and are therefore particularly well-suited to dToF systems requiring precise photon timing. APDs function as amplifying photodetectors and are used in various ToF and LiDAR systems. CMOS pixel arrays form the basis of modern iToF sensors and enable high resolution as well as extensive integration of signal processing. LiDAR does not describe a sensor or measurement technology, but rather a system architecture. Typical systems scan their surroundings by sequentially emitting and analyzing individual light pulses, point by point. This scanning principle enables long ranges and high distance accuracy. In contrast, CMOS-based iToF cameras capture entire scenes simultaneously and provide depth information for all pixels in parallel. Equating LiDAR with dToF therefore does not reflect the differences between the two system concepts.

dToF and iToF describe only the measurement method. It is on this basis that different application systems such as LiDAR, distance sensors or 3D cameras are developed.



From specialized solutions to industrial cameras

Limited resolution, sensitivity to ambient light and difficulties with moving objects often made it necessary to use more complex and costly 3D technologies. Current iToF systems overcome many of



Current iToF cameras deliver higher pixel resolutions, which improve the capture of spatial detail, while the combination of integrated depth processing and a global shutter facilitates the imaging of dynamic scenes with reduced motion artefacts.

these limitations through advances at the system level.

Modern sensor architectures combine higher resolutions, global shutter technology, integrated memory and extensive signal processing directly within the sensor and camera system. It is the consistent further development of all system components – from the illumination and the sensor to signal processing – that determines the performance of modern iToF systems.

A key development step is the shift of depth calculation into the sensor and the camera. Depth images, intensity values and quality information can be generated directly within the system, rather than processing large volumes of raw data externally. This reduces data loads, shortens response times and simplifies integration into industrial applications. At the same time, modern storage and evaluation concepts improve the

capture of moving scenes, whilst higher modulation frequencies and optimized NIR illumination enhance measurement quality and robustness.

As a result, iToF is increasingly establishing itself as a cost-effective 3D technology for a wide range of industrial applications. The key factor here is not a single component, but the consistent integration of all system components into a high-performance overall system.

The power resides in the overall system

A look at dToF, iToF, LiDAR, SPAD and similar terms reveals one thing above all: ToF is not a single technology, but an entire class of different approaches to distance and depth sensing. The characteristics of these systems are determined not by the choice of measurement method alone, but by the specific

implementation of the light source, receiver and data processing.

Whilst dToF demonstrates its strengths particularly at long ranges and with precise photon timing, modern iToF systems benefit from wide-area data acquisition, a high degree of integration and the ability to capture depth information for entire scenes in parallel. Advances today are driven not primarily by new measurement methods, but by the increasing integration of sensor technology, processing and software into application-optimized complete systems.

A recent example of this development is modern iToF 3D cameras such as Nion from IDS Imaging Development Systems. With the depth calculation already integrated into the high-resolution sensor, NIR illumination in the daylight-independent 940 nm spectrum and signal processing directly within the system, data volumes can be reduced, response times shortened, and motion artefacts minimized. At the same time, the integration effort for users is reduced.

This has led to the development of affordable 3D cameras that can handle many traditional short-range 3D tasks and make ToF accessible for a significantly broader range of applications. The real innovation here lies not in a new measurement method, but in the systematic optimization of the entire system. This is precisely why, now more than ever, it is true that “ToF is not equal to ToF”.

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