WHITE PAPER

Applications for Time-of-Flight Cameras in Robotics, Logistics and Medicine

There are different techniques for measuring objects and scenes in 3D. One of the most promising is known as Time-of-Flight, or ToF. Our earlier publications explored the fundamentals of ToF Camera technology, including extensive comparisons between the individual 3D technologies. The following will take a closer look at the Time-of-Flight process and explain the applications for which it is best suited.

Content

1. Introduction to ToF Camera Technology

One major difference between 2D and 3D technologies is the type of gathered data. Both quantify the light coming from the subject of the image, but the 3D technology also provides depth values for the recorded scene or object. This opens up a completely new range of opportunities for solving complex tasks — especially in the fields of logistics, robotics and factory automation as well as in the medical field.

The Time-of-Flight (ToF) process is a very efficient technology for generating depth data and measuring distances. A ToF Camera provides two kinds of information for each pixel: the intensity value (indicated as a gray value) and the distance between the object and sensor, known as the depth value.

There are two different ways for Time-of-Flight measurement: continuous wave and pulsed Time-of-Flight.

The continuous wave Time-of-Flight method is based on measuring the phase shift between emitted and reflected light of a brightness-modulated light source.

Cameras working with the pulsed Time-of-Flight method determine distances based on the time delay between the emitted and the reflected light pulse.

A Time-of-Flight Camera is a compact system without movable parts and consists of:

- an active integrated light source,
- an integrated lens and
- a Time-of-Flight sensor.

The camera‘s light source emits the light pulses. This light hits an object and is reflected back towards the camera’s sensor. The integrated lens ensures that the reflected light strikes the sensor. In simple terms, the depth value is calculated for each individual pixel by measuring the time required by the light to pass from the camera to the object and back to the sensor (see Fig. 1).

This process provides a real-time multipart image which consists of a point cloud, a depth map, an intensity image and a confidence map — all captured at the same moment.

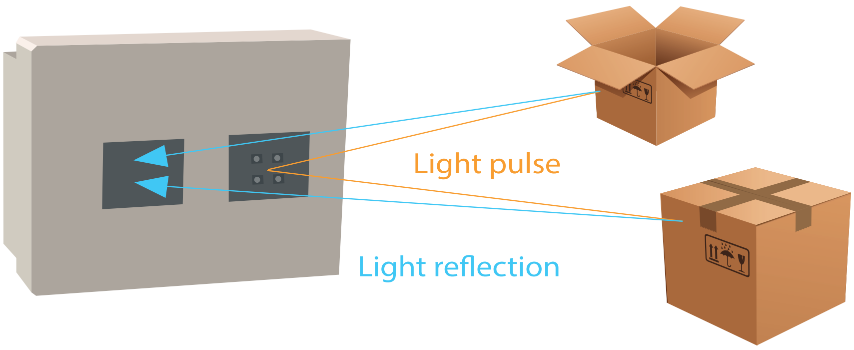

Figure 1: Functional Principle of Time-of-Flight Cameras

1.1 Typical Application Areas for Time-of-Flight Cameras

Time-of-Flight Cameras are especially well suited for applications that require a large working distance, high speed and low complexity, and where those requirements outweigh the need for µm-precision. ToF Cameras are also a relatively affordable option from a budgetary standpoint.

ToF Cameras represent the perfect option for volume measurement in logistics, palletizing and depalletizing tasks as well as for autonomous vehicles in logistics and production environments. There are also new and exciting tasks for Time-of-Flight Cameras in the medical field, namely for the positioning and monitoring of patients. In an industrial environment, the relative low precision of the depth values makes ToF systems primarily suitable for tasks that do not require extreme precision, such as pick-and-place applications involving larger objects, robot control functions, robot-based factory automation and autonomous vehicles.

ToF applications can be divided into two fields: gesture-controlled and non-gesture controlled applications. The gesture-controlled applications include all applications in which a person is intended to use gestures to communicate with the device, such as in the interaction between a robot and a person, or to control an entertainment application in a vehicle.

Non-gesture controlled applications are particularly common in logistics, medicine and automated guided vehicles. In these applications, cameras initially capture an image, and then an algorithm assesses its characteristics. This allows for scenes to be monitored or the volume and position of objects to be determined.

2. Differentiation from Other 3D Technologies

Just as there are area and line scan cameras for 2D image processing, each with their own strengths and weaknesses, there are also other technologies for 3D image processing beyond Time-of-Flight, such as the following:

- stereovision and structured light as well as
- laser triangulation.

Each of these technologies relies on a different principle for measuring the third dimension. The technologies also supplement one another. The requirements of the application at hand determine which technology is best suited.

Our White Paper "2D or 3D Camera? Which 3D Camera Technology Fits Your Application?" compares the individual 3D technologies extensively.

2.1 Stereovision and Structured Light

The stereovision process works according to the same principle as a pair of human eyes. Two 2D area scan cameras capture two 2D images of a scene from various positions. Using the triangulation principle and other provided information, a 3D image can then be calculated out of the two images.

The images are rectified based on their camera position relative to one another and knowledge about the projected geometry. After the rectification, a matching algorithm is used to search for corresponding points in the right and left image and a depth image of the scene is generated.

The working distance at which this process functions depends on the baseline – the distance between the cameras – and therefore varies.

The performance of a stereovision system can be improved by adding structured light. This involves projecting structured light from a light source onto the scene to help the system achieve more precise measurements. At the same time, this process reduces the disadvantages of stereovision related to homogeneous surfaces and low light. Calibrating the projector with the camera even makes it possible to dispense with the use of a second camera.

2.2 Laser Triangulation

The laser triangulation process is a combination of a 2D camera and a laser line or laser dots emitted by a projector. This laser line is focused on the object being measured, while a 2D camera observes the line emitted by the laser. If there is a change in distance between the object of measurement and the sensor, the angle of the laser line changes, and with it its position in the camera image. A trigonometric function is applied to the change of position to calculate how far the object is located from the laser projector. The camera determines the position of the laser dot in the image. The distance between the sensor and the object is then calculated based on that position within the image.

As already mentioned above, there is no single perfect 3D technology to solve all vision applications that need 3D data. The user must always consider which of the various technologies fit the application most effectively.

Table 1 compares how the individual technologies perform in terms of given application key criteria:

	Stereo-vision	Structured light	Laser triangu-lation	Time-of-Flight Cameras
Range	Medium	Medium	Low	High
Resolution	Medium	Medium	Varies	High
Depth accuracy	Medium to high	High	Very high	Medium
Software complexity	High	Medium	High	Low
Real-time compatibility	Low	Medium	Low	High
Behavior in low light	Weak	Good	Good	Good
In sunlight	Good	Weak	Medium	Medium
Compactness	Medium	Medium	Weak	High
Material costs	Medium	High	High	Medium to low
Total operating cost	High	Medium	High	Medium to low

Table 1: Comparison of various 3D technologies

3. Benefits and Challenges for ToF Technology

The biggest benefit of ToF Cameras is that they are compact and affordable, yet less complex than other 3D cameras. This makes it very easy to separate between objects within a scene, a key step to interpreting them. Beyond this, a ToF Camera requires neither contrast nor edges or corners to work, and can be used on the fly, as objects move past.

Overview of strengths and weaknesses of ToF Cameras:

+ The scene is recorded all at once and doesn't have to be scanned
+ High speed
+ 2D and 3D images in a multi-part image
+ High X/Y resolution
+ Compact system without moving components
+ Works very well at low light
+ Eye safety is provided
+ No structure or contrast required
+ Large working distances are possible with a sufficiently strong light source
+ Low overall system costs
+ High real-time capability

– Problems with mirroring and highly reflective (uncooperative) surfaces
– Sensitive to scatter light and multipath interference

4. ToF Camera in Robotics

Time-of-Flight Cameras are very well suited for bringing sight to robots as well as a, human' sense of orientation. It opens the door for future robotics applications to be designed significantly more efficiently, which in turn opens up new fields of application. For example, an improved ability to detect objects within a space and circumnavigate those objects creates new possibilities for mobility.

4.1 Human Machine Interface (HMI) and Machine Safety

When it comes to the cooperation between humans and robots, the central consideration is always: safety. In tight working environments in particular, the robots must recognize machines and their movements and be able to react immediately to avoid injuries. ToF technology makes this easier. Real-time compatibility and the speed of a ToF Camera allow the robots to perceive movement around it and stop in time when pre-defined minimum safety distances are violated. The robot can also track human movements, allowing them to work parallel to humans. Robots can provide parts as needed and take them when given, monitor processes, refill empty stocks and identify assembly and material errors. In short: They can support humans in their work.

4.2 Factory Automation

In the area of factory automation, ToF Cameras are primarily used in pick-and-place tasks and for assembly work. Here the robots are outfitted with one or more ToF Cameras. This allows the robot to scan its environment, identify and grasp objects, transport them to another location and then set them down or mount them on something.

ToF Cameras are also frequently used in the quality assurance process. They can also identify improperly dimensioned objects and shapes and recognize chips or holes in an object. This helps prevent defective objects from entering into the production process.

4.3 Automated Guided Vehicles (AGVs)

Automated Guided Vehicles (AGVs) can also benefit from the Time-of-Flight technique. One or more ToF Cameras generate a real-time image of the surroundings, allowing the AGV to review its environment quickly for hazards or to follow a person. A ToF Camera can be used to stitch together multiple individual snapshots of the environment, after which the AGV can then use this ‚map' to navigate the space. This offers massive benefits in terms of automation of production and logistics: Processes can be accelerated, which in turn increases efficiency.

AGVs can be used in production, for example, to fetch parts from the warehouse automatically for the next production step and bringing them to the workstation at precisely the moment they are needed. The AGV can then also bring the finished parts just-in-time for the next work step or to the shipping department for packing and shipping. The AGV knows at all times which part is needed and ensures that the work can run smoothly. Obstacles, such as an object in its path, are not a problem for the AGV. Thanks to the ToF technology, the AGV recognizes the obstacle and simply drives around it to reach its destination.

AGVs were previously outfitted with laser scanners instead of ToF cameras. While these scanners have the benefit of fulfilling the safety requirements specified in SIL[2], they are poorly suited for spatial orientation. Laser scanners can only depict one plane, and hence while they identify that an obstacle is present, they do not provide options for reacting to the hurdle. As a result: the AGV stops completely once the laser scanner identifies an obstacle. This emergency step must be manually resolved by human workers, which represents an interruption in the workflow.

5. ToF Camera in Logistics

ToF Cameras used for logistics are typically applied in the measurement, identification and location of objects and packages, as the cameras can provide this key information without delaying processing. Because they offer a variety of different skills, they can be used in a flexible range of working environments. Sample applications include use above a conveyor belt or packing table, mounting on a conveyor vehicle or above a portal through which large packages are moved using a fork lift.

[2]SIL stands for «Safety Integrity Level» and refers to a standard to assess the reliability of safety functions in electronic systems.

Figure 3: ToF technology can help increase efficiency within the logistics field.

5.1 Handling of Pallets

Palletizing and depalletizing are among the most time intensive of logistics tasks and can provide a major boost if automated to work without disrupting the flow of operations. While these tasks might not seem particularly complex at first glance, closer inspection reveals more challenges than might be expected. A palletizing and depalletizing task is not purely about loading or unloading cargo. A palletizing robot needs to determine precisely where the objects to be picked up are located, how large they are and their positioning relative to one another to allow for an optimal grip position and to best use the existing space.

These tasks cannot be resolved using traditional 2D image processing, and humans also struggle with the task, as it is often laborious and time-consuming, especially when the objects are extra-large or heavy.

3D solutions here must be able to ‚see' in real time like a person, including the location, size and gripping position; minute-long pauses to determine which object should be moved next are disruptive. ToF Cameras are perfect tools for this task. The cameras identify the situation at a glance and calculate the necessary parameters on the fly.

5.2 Volume Measurement

Volume measurement for individual objects is another major task of logistics. As described in section 5.1, volumes must be measured and the position and size of objects must be assessed. Alongside palletizing, volume measurement is one of the most important factors to determine freight or shipping costs. The volume of the packed units is measured, and then freight costs are determined based on that data. Automation of this process can bring significant savings, as freight costs tend to be mere estimates and/or based on information from the sender, which can be imprecise.

Other highly interesting fields of application that could benefit from volume measurement and location detection based on 3D data include automated warehouse management and efficient filling of containers and airplanes. To avoid void spaces during transport and fully utilize the loading space, volumes are measured based on 3D data and that information is used to find an optimal configuration of the freight goods.

3D data and robot arms can make automated warehouses run more efficiently, as they simplify the process of picking and storing goods. This in turn streamlines processes, saves time and reduces error rates during picking and storage.

6. Time-of-Flight Cameras in Medical Applications

Time-of-Flight Cameras are outstandingly well-suited for supplemental medical imaging processes. 3D image data opens up a fascinating range of potential applications for patient monitoring and positioning, as well as body measurements and x-ray diagnostics

6.1 Patient Positioning and Monitoring

ToF Cameras help position patients optimally for MRI or CT scans (magnetic resonance imaging or computed tomography). Point clouds from a reference image are compared with a point cloud reflecting the patient's current position. The objective is to move the patient into precisely the same position as the one captured in the reference image.

ToF Cameras are also used in intensive care rooms. They are increasingly replacing classic surveillance cameras, as the extra depth data allows nurses to remotely monitor both the room itself and each patient inside it. The ToF Cameras detect the position of the patients even under the covers and — thanks to intelligent algorithms — can even warn about oncoming epileptic attacks or alarming vital parameters.

6.2 Volume Measurements

ToF measurements are also used in x-ray diagnostics, namely whenever volumes must be determined to calibrate the correct radiation dose. On standard x-ray machines, the x-ray technician sets the radiation dose manually. The default value — maximum radiation level — is often selected to ensure the best possible image. Current research shows however that x-ray imaging is best performed conservatively, i.e. with a lower radiation dose. For this to work, one or more ToF Cameras are used to determine the volume and precise position of the patient‘s body, with the 3D data then used to calculate the optimal dose.

7. Summary

The market for Time-of-Flight Cameras is constantly growing, with the path clear for far-reaching usage in the future. There are already many uses for ToF Cameras now: gesture-controlled entertainment in cars, logistics tasks, robotics and even medical applications. The implementation of image processing solutions in these fields will further stimulate demand for ToF technology. Time-of-Flight is especially well-suited for applications that don‘t need extreme levels of precision, but do need very simple and compact systems at moderate costs.

The benefits of ToF Cameras compared to stereovision and laser triangulation come primarily in speed, compactness and simple integration and feature options. It should be noted that there is not just „one“ superlative technology for 3D applications. Nor is 3D always better than 2D for some applications. Image processing and the applications in which it is used are typically so complex that the user of any application needs to decide on a case-by-case basis which fits best — reflecting the individual requirements, the ambient conditions and the available budget.

It‘s important to always monitor the total cost of ownership for these investments throughout their life cycle, not just the cost of the individual components. 3D system installation and software solutions can involve significant costs during initial setup, despite the nominally affordable components themselves.

Yet ToF technology is improving constantly and can already be used in many fields of application to improve efficiency and cut costs. This tendency is only expected to increase in the coming years.

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