Laser Light Absorption by Atmospheric Oxygen for 3D Imaging

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ABSTRACT

Researchers in Espoo, Finland have developed a 3D camera using light absorption of atmospheric oxygen with a current-tunable single frequency distributed feedback laser. The laser provides active illumination for the laser light absorption of oxygen at 761 nm while a silicon-based image sensor captures the light. The designed 3D camera creates a novel solution in 3D imaging for short to medium ranges (0 - 10 m), complementing the benefits of both light detection and ranging (LiDAR) and stereo vision camera techniques. With the oxygen absorption design, researchers achieved a distance accuracy of better than 4 cm between measuring distances of 4 m and 10 m to demonstrate the potential of this new 3D imaging method.

3D CAMERAS

The need for practical and functional 3D cameras is steadily increasing as automation and mobile applications demand cheaper, more compact, and more accurate techniques. From small mobile devices to automatic industrial robotic applications, 3D cameras are critical for short to medium ranges between 0 and 10 meters in logistics and factories.[1]

There are two main methods for 3D capture devices: light detection and ranging (LiDAR) systems and stereo vision cameras. LiDAR uses time-of-flight (TOF) data from a laser or another light source to find distance measurements for a single-point system or imaging systems using a TOF sensor array (Figure 1). TOF sensors use the time difference from the light emission to its return to calculate the distance measurement. A stereo vision camera is a more passive system using triangulation with multiple cameras to determine the specified distance and to create a 3D image.

Figure 1. Example 3D imaging of a warehouse using scanning LiDAR techniques.

PROBLEMS AND GOALS

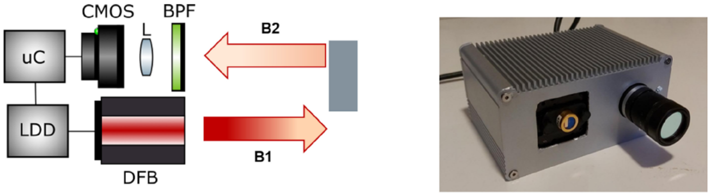
LiDAR systems can have a very high field-of-view (FOV) due to their rotational scanning nature, creating thick point clouds with high frame rates with one or multiple lasers.[1] However, the scanning rotation can cause issues for high-volume applications. With mechanical parts in a rotating motion, reliability can be a problem with long-term applications, and commercial devices with rotating scanning systems can be expensive. Low-cost scanning LiDAR systems are commercially available, but they a have significantly lower number of points in the 3D point cloud leading to a lower resolution.[1] Stationary TOF systems have recently emerged for 3D applications without any moving parts, making them an interesting alternative to scanning LiDARs using TOF methods.

Ambient lighting conditions can affect the performance of stereo vision cameras as well as LiDAR devices. Bright lighting negatively affects LiDAR due to the sensitive detectors used, decreasing the resolution or accuracy of the data. Some stereo vision cameras use an active pattern projection in dark environments to increase 3D imaging accuracy.[1] Stereo vision cameras and LiDAR are used for their respective applications depending on the requirements and conditions, but typically stereo vision cameras have a lower cost-per-pixel price point overall.

Stereo vision cameras tend to have high-resolution 3D images and can enable a wide FOV without movement, although not the 360º range that is achievable with scanning LiDAR. With either method, there is room for improvement in short to medium ranges (0 - 10 m) and in price. A novel solution is needed with an active measurement system, compact design, and no moving parts to keep prices low and reliability high for indoor 3D imaging.

METHOD

Researchers from the VTT Technical Research Centre of Finland have developed a 3D camera based on laser light absorption utilizing atmospheric oxygen absorption lines at 761 nm. Ranging systems have previously been designed using light absorption, however, using atmospheric absorption for 3D imaging is a novel proposal for imaging and camera applications. Typically, distributed feedback lasers (DFBs) are used to probe the absorption lines of the desired chemical compound or element. The imaging sensor or complementary metal-oxide-semiconductor (CMOS) imager and the laser are both readily available and mass-producible.[1] The diagram of the 3D camera prototype can be seen in **Figure 2**.

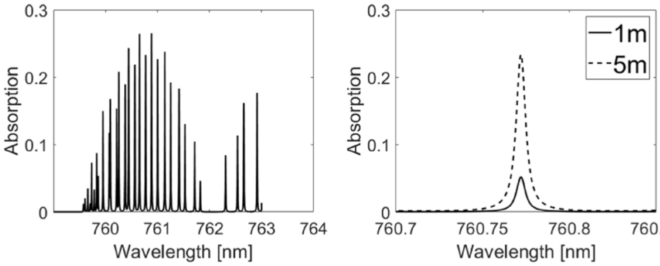


a) b)

Figure 2. a) Block diagram of the 3D camera prototype. uC = microcontroller, LDD = laser diode driver, DFB = distributed feedback laser, BPF = band pass filter, L = lens, CMOS = complementary metal-oxide-semiconductor imager, B1 = diverging laser output beam, B2 = light reflected from an object. The light beam is attenuated by molecular oxygen. b) Figure of the prototype in aluminum enclosure, showing the laser output and the camera objective.[1]

An Arduino microcontroller and the laser diode driver (LDTC0520) from Wavelength Electronics control and adjust the laser current and can vary the emitted wavelength to scan the absorption lines or further tune the center wavelength of the DFB laser. The laser temperature is also stabilized with a temperature controller to ensure the temperature and wavelength are fixed. The DFB laser output was 30 mW for the research and has a specified linewidth of less than 10 MHz, which is critical for atmospheric absorption spectroscopy of this nature. The CMOS camera has a resolution of 484 x366 pixels and reads the reflected signal from the divergent (6 x 26 degrees) laser output to create an image.[1]

Atmospheric oxygen is chosen for its stable concentration and the ability to use low-cost silicon-based imaging sensors. Many absorption lines are viable for imaging, but the absorption line centered around 760.77 nm is used as it is free from absorption by other molecules often found in the atmosphere such as ambient carbon dioxide and water vapor. Using the strongest absorption line of oxygen is best suited at short to medium ranges (0 - 10 m). The absorption of water vapor around 761 nm is around four orders of magnitude lower than oxygen, and no carbon dioxide absorption lines exist in this region.[1] The signal attenuation at a larger distance, as well as the oxygen absorption spectrum, can be seen in **Figure 3**.



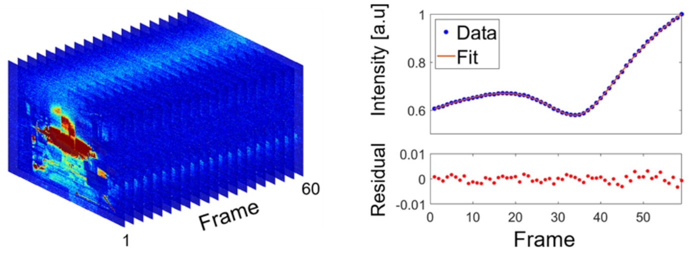
a) b)

Figure 3. a) Simulated oxygen absorption spectra around 761 nm wavelength at 5 m distance (10 m total propagation). b) Simulated absorption spectra of the absorption line around 760.77 nm for 1 and 5 m distances (2 and 10 m propagation), respectively.[1]

With the selected absorption line for oxygen, the limitation of this design is 75 m. For longer distances, weaker absorption lines could be used with adequate illumination power for the laser. With oxygen absorption, the calculations assume a constant concentration of molecular oxygen in the air: ~20.9% oxygen in ambient air. Thus, the developed system is limited to environments with very few deviations or different concentrations for accurate oxygen measurements, or frequent calibration would be required.

Two wavelengths for illumination can be used to produce a 3D image, but this can generate rift and jitter in the laser wavelength, creating large errors in the distance measurements. By illuminating the scene with multiple wavelength points over the whole absorption profile and recording the absorption spectrum, the laser drift and jitter problem can be avoided. Here, researchers swept the current and emitted wavelengths over the absorption profile of oxygen. The laser is brought below the lasing threshold to capture a dark frame from ambient light, and then the injection current is gradually increased to generate a total of 60 illuminated frames. The frames constitute a single data cube, making a single 3D frame. This frame-cube generation can be seen in **Figure 4**. Because the current tuning is swept, both the laser output power and wavelength increase, creating a linearly increasing component for the detected absorption.

In the calculation software to create the 3D frame from the data cube, several approximations are taken to focus on extracting a stable and precise estimation of the absorbance rather than an accurate reading which can be corrected using known distances.[1]

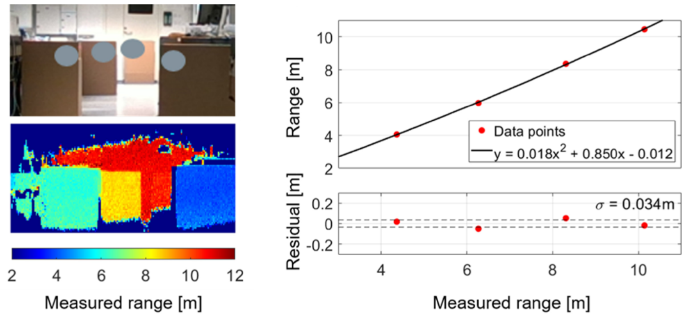


a) b)

Figure 4. **a) An example of a recorded data cube. b) An example absorption signal extracted from a single pixel of the data cube consisting of 60 illuminated frames. Blue dots are normalized pixel intensity data, the red line is the result from the fitting algorithm and the red dots are the residual (data - fit).[1]**

RESULTS

With this oxygen absorption 3D imaging technique, researchers measured the accuracy and noise of the ranging of the 3D camera in an indoor test area using cardboard boxes as test targets placed between 4 m and 10 m. This testing setup can be seen in **Figure 5** as well as calculated and reference distances. The figure below includes an RGB image of the test area setup and a heat map plot of the 3D image.

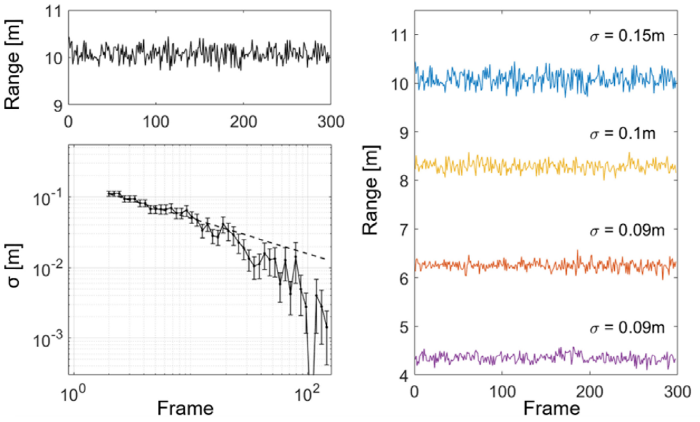


a) b)

Figure 5. **a) RGB image of the test area with selected test points marked as gray circles and a heat map plot of the 3D image. The RGB image was taken with a separate camera. The target with the largest distance was close to a wall at a similar distance and thus is not shown as a rectangle. b) Correlation plot of the calculated distance vs reference distance measurement with 2nd order polynomial fit and residual. Sigma denotes the mean absolute error of the measured signal after fitting.[1]**

The distances to the boxes were measured for reference using a commercial range finder with an accuracy of ±2 mm. Because of the diverging axes of the laser beam, the illuminated area was elliptical. The 3D camera resulted in a total of 9183 pixels that were fitted, and the image in **Figure 5** is formed by binning 9 pixels and taking an average of 10 consecutive 3D frames.[1] Comparing the calculated ranges to the measured ranges, the 3D camera ranges were within 0.3 m without any correction. This calculation used the measured absorption of oxygen in ambient air, known absorption strength, and assumed 20.9% oxygen concentration in the air. Once a second-order polynomial correction curve is fitted in the data, the absolute error is reduced to 3.4 cm, as seen in **Figure 5**b.

300 3D frames were captured with an image acquisition time of 400 s to study the noise and stability of the range measurement using Allan deviation analysis. The Allan plot for the furthest distance of 10 m is shown in **Figure 6**a. This Allan plot is shown as averaged 3D frames at 0.73 Hz frame rate instead of averaged time.

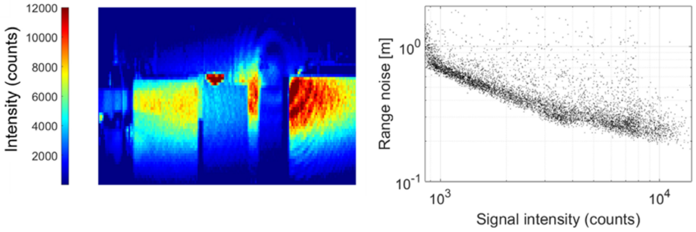


a) b)

Figure 6. **a) Allan deviation analysis for a binned pixel. Range to target was 10 m. Total of 300 3D frames were recorded during with 400 s acquisition time. b) shows the time series of the ranges for the four test targets. The range values were binned from 9 pixels around the target area. Sigma denotes standard deviations of the range values.[1]**

The dashed line in **Figure 6** shows the fully uncorrelated noise that decreases as 1/√N, where N is the number of measurements averaged. By averaging the 3D frames, precision below 1 cm was achieved.[1] It is also observed that the signal-to-noise ratio of the return signal is higher at shorter distances, but longer distances have a larger absorption signal to compensate. Pixel binning, as well as frame averaging, reduced the noise by a factor of 3.

Figure 6 shows the intensity map of the 3D image from **Figure 5**a as well as a scatter plot of the range noise. This scatter plot shows the reduction of noise as 1/√N, where N is the intensity as counts for a given pixel.



a) **b)**

Figure 7. a) Intensity map of the 3D image of Fig. 4(a). b) Scatter plot of the range noise. y-axis is the single pixel standard deviation during the 300 3D frames. x-axis is the signal intensity as counts.[1]

With the 3D cube used to create a 3D image, researchers successfully demonstrated the ability to use laser absorption of atmospheric oxygen for 3D imaging. This design was demonstrated for a 4 - 10 m range and provides a compact and low-cost solution to complement LiDAR and stereo vision cameras.[1] Performance of the design depended on pixel number division of light, maximum detection range, and reflectivity of the targets in the detection range. Further studies can explore sensors with higher sensitivity and performance and a more evenly distributed light source. The imaging frame rate of 0.73 Hz could be increased to a frame rate closer to that of stereo vision cameras (10 - 20 Hz) but would require a more efficient data processing setup than the one presented in this experiment. Researchers demonstrated 3D imaging with a distance accuracy of better than 4 cm between 4 and 10 m based on laser light absorption of atmospheric oxygen at 761 nm.

WAVELENGTH'S ROLE

With laser absorption of atmospheric oxygen, current control and temperature stability are critical for reliable and repeatable absorption spectra. The linewidth, temperature, and current injection of the laser must have precise control as other molecules in the atmosphere can distort and cloud the absorption spectrum of the experiment. To control the laser with a linewidth of less than 10 MHz, researchers used Wavelength Electronics' LDTC0520 laser diode driver and temperature controller. The LDTC0520 drove current to the laser and controlled the temperature for the precision laser absorption system. With a size of approximately 6 x 7 x 3 cm, the LDTC0520 aided the compact design of the 3D camera.

The LDTC0520 provides up to 500 mA of current to the laser with noise as low as 7.5 µA RMS. The temperature controller portion of the LDTC0520 provides up to ±2.2 A to a thermoelectric cooler or resistive heater with temperature stability as low as 0.002ºC over one hour. The driver/controller combo contains safety features to protect the laser and the user: brownout protection, laser current limits, heat and cool current limits, laser and temperature setpoints, delay, and slow start.

With the combined temperature controller and laser diode driver, the LDTC0520 module is compact and easy to use with controls and indicators on-board for simple plug-and-play operation. The LDTC0520 combines the proprietary FL500 laser diode and ultra-stable WTC3243 into one compact module for trouble-free operation. The compact design of the LDTC0520 can fit into most portable or benchtop equipment for oxygen or other chemical absorption using laser illumination for 3D imaging in the lab or out in the field.

REFERENCES

1. Kääriäinen, T., Seppä, J., 3D camera based on laser light absorption by atmospheric oxygen at 761 nm. *Optics Express*. 2024, **32** (4), 6342-6349. https://doi.org/10.1364/OE.510679

USEFUL LINKS

- LDTC0520 **Product Page**

PERMISSIONS

No changes were made to the captions or images. They are presented here in their original form.

PRODUCTS USED
LDTC0520 Laser Driver / Temperature Controller

KEYWORDS

3D camera, laser light absorption, atmospheric oxygen, distributed feedback laser, active illumination, ranging, field of view, lidar, stereo camera, laser diode driver, temperature controller, LDTC0520

REVISION HISTORY

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REVISION	DATE	NOTES
A	May 2024	Initial Release