## Time of Flight Cameras Distance Error Corrections

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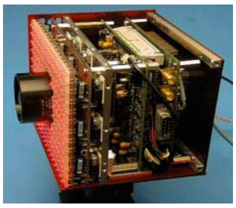
ToF cameras are relatively new devices, able to deliver simultaneously two images of a scene:
- an **amplitude image**(somehow a 'classical' image)

- a **'distance' image**( the value of each pixel is proportional to the distance of the object to the camera)

That is why these cameras are also called **3D cameras**.



Nevertheless, at present, these devices are still in their infancy.



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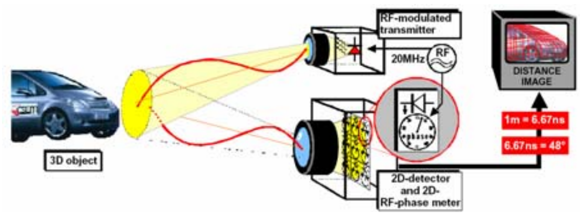
## The ToF principle



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## OUTLINE

- The context of research done at LAPI
- The progress towards robust and correct measurements
- The errors and their origin for the distance image
- The main contribution: a classical model for the signal
- Results
- Further research
- Fields of applications
- About an important medical application
- Some more words on LAPI's activities

(color image processing, medical image processing, software tools for digital photography, algorithms for detectors of LHC experiments, high speed computer networks for ATLAS-LHC, summer schools)

# The context of research done at LAPI

UPB (University POLITEHNICA Bucuresti) is a partner of the IST-34107 project of the Sixth Framework Programme of the European Comission

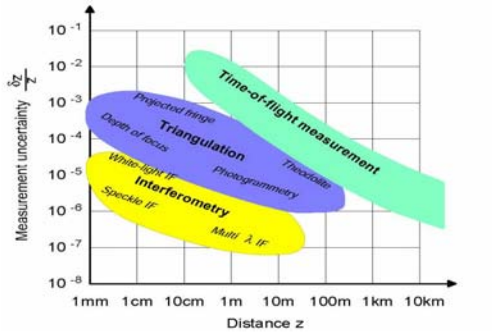
Project tile: **Action Recognition and Tracking Based on Time of Flight Sensors**

Project acronym: **ARTTS**

The leader of the project is the University of Luebeck( Germany) by its Institute of Neuro and Bioinformatics( project leader Erhardt Barth)

Starting Date: October 2006






Performance map of conventional optical 3D systems
Diagram taken from '**3D Time-of-Flight Distance Measurement with Custom Solid-State Image Sensors in CMOS/CCD-Technology' by** Robert Lange granted to [SC1]

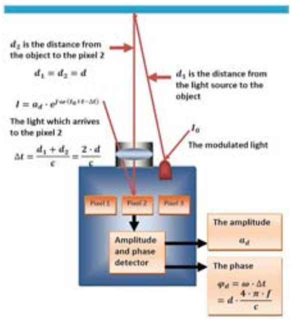


## ToF cameras on the market today (or in a recent past)

| Commercial Products of 3D Range Camera (selection as of May 2006) | DMC100 | Development kit | SR3000 | Prototype | A2 |
|---|---|---|---|---|---|
| Manufacturer | 3DVSystems Inc. | Canesta Inc. | CSEM AG | Matsushita Electronic Works | PMDtec GmbH |
| Wavelength [850nm] | N/A | 785 | 850 | N/A | 870 |
| Modulation Frequency [MHz] | N/A | 52 | 20 | N/A | 4 |
| Illumination Power [W] | N/A | <1 | <1 | N/A | 20 |
| Pixel Resolution (Horizontal/Vertical) | 510x492 | 64x64 | 176x144 | 128x123 | 64x16 |
| Distance Accuracy [cm] | >0.3 | >2 | 4.6cm@7.5m | N/A | 10@40m |
| Maximal Frame Update Rate [Hz] | 60 | 30 | 50 | 15 | 60 |
| Field of View (Horizontal/Vertical) [°] | 45x35 | 30, 55, or 80 | 48X40 | 60x45 | 52x18 |
| Non-ambiguous Range [m] | 0.3-2.5 | 5 | 7.5 | 7.5 | 40 |
| Connection | Firewire, RS232 | USB 1.1 | USB 2.0 | USB2.0 | Ethernet |
| Output | X,Y,Z, intensity | X,Y,Z, intensity | X,Y,Z, intensity | N/A | X,Y,Z |
| Website | 3dvsystems.com | canesta.com | swissranger.ch | nais-e.com | pmdtec.de |



## The progress towards robust and correct measurements




The principles of the Time of Flight camera

**Problem:**

The distance image is false

**Solution (partial):**

- filtering distance image

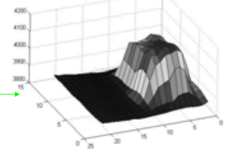
- filtering method: adaptive neighbourhood
  - very effective in filtering the noise
  - preserving contours



## ToF Systematic Errors

Due to the fact that ToF cameras are active systems (i. e. own light source) the received reflected light decreases with( aprox.) square of the distance
The problem of error sources as regarding distance image is much more complicated and will be the main subject of today presentation.

ToF Intensity Image



ToF Distance Image



## First aim of the research

- To correct the errors (both in amplitude and distance)
- To use each one of the image for the correction of the other
- [to extend the camera for color images]



Intensity image correction using distance image:

- for objects are blackish (intensity decreases with the square of the distance)

- correction proposed: pixelwise

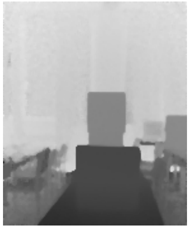
$$a'(p)=a(p)*d^2(p)$$

where a(p) is the uncorrected intensity in the pixel p
a'(p) is the corrected intensity in the pixel p
d(p) is the distance image in the pixel p

Correction without filtering

Correction with filtering





Before Adaptive Neighbourhood Filtering

After Adaptive Neighbourhood Filtering



Originale

Filtrée FCVA

Bruitée



Originale

Filtrée FCVA

Filtrée FAHM

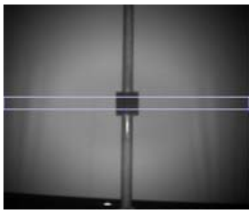
Originale

Filtrée FANPN

Filtrée FCVA

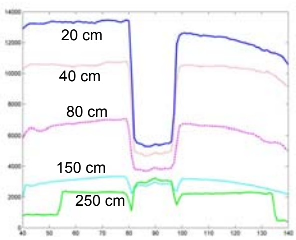


## The errors and their origin for distance images



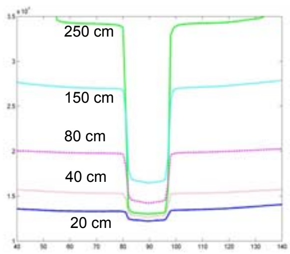
Experimental setup: a black square is placed at a constant distance from the camera. Behind it a white screen is moved at different distances.





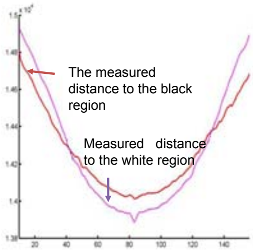

The detected light amplitude by the pixels in the marked rectangle in the previous image. The distance between the black rectangle and the white screen is marked for each curve in the figure






The measured distance to the objects included in the white rectangle presented in the previous image**.** For each curves the white screen is placed behind the black square at the distance marked in figure

The Experimental setup: a black strip is painted on a white screen




Plot of the measured distances along the blach and white vertical lines



## LAPI main contribution to improve distance image

### Fălie Model

Notations:

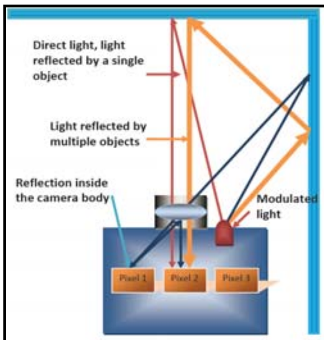
- p=(i,j) a pixel
- $I_m(p)$ the measured signal at the pixel p ideally a sinusoid of a given frequency(20MHz) with an amplitude $a_m(p)$ and a phase $\varphi_m(p)$. In classical notations

$$I_m(p)= a_m(p) * e^{j\varphi_m(p)}$$

- $I_d(p)$ the useful signal we look for, i. e. the reflected direct light from the object in the scene corresponding to the pixel p
- $I_p(p)$ the perturbative component of the $I_m(p)$ mainly due to the reflexions(1) inside and (2) outside the camera

$$I_p(p)= I_{r1}(p) + I_{r2}(p)$$






The object in the scene is iluminated directly by the modulsted light and indirectly by the light reflected by other objects. Inside the camera body the incoming light is reflected by the cip surface to the lenses surface and back to the cip



The main statement of the model is expressed in the relation:

$$I_m(p)=I_d(p) + I_p(p) \qquad (1)$$

which has to be understood as a relation between complex quantities

[In many of the formulae we will drop the argument p (pixel) maintaining only when needed for clarity]

How to solve one equation with two unknowns:

- Mathematical point of view ?
- A physicist/engineer point of view: find out/invent a second equation

(add data)

In our case: let the same scene with the same conditions, but just one change: the useful signal value in the pixel p. This modification very likely will have no seasable influence on $I_p(p)$ so we can add a second equation:

$$I'_m(p)=I'_d(p) + I_p(p) \qquad (2)$$

and $I'_d(p)$ has the same argument as $I_d(p)$

From eq(1) and eq(2) one gets:

$$I'_m(p) - I_m(p)=[a'_d(p) - a_d(p) ]*e^{j\varphi_d(p)}$$



What was described previously means two records of the scene.

Is it indeed necessary?

Not exactly: $I_p(p)$ has almost only very low spatial frequencies. So, in general, if p and p' are two neighbouring pixels or small regions, then $I_p(p)= I'_p(p)$.

The correct value for two points at the same distance but with different intensities can also be deduced from above.



## Parasitic Component Determination: $I_p$

We start with the equation

$$I_m(p)=I_d(p) + I_p(p)$$

We can imagine the same scene illuminated differently on the small region corresponding to the pixel p in the image so that

$$a_{d1}(p)=k*a_{d2}(p)$$

where a stands for the modulus of I

Because $\varphi_d(p)$ only depends on distance and this doesn't change, we also have

$$I_{d1}(p)=k* I_{d2}(p)$$

$I_p(p)$ remains the same. So we get

$$I_{m1}(p) – I_{m2}(p)=I_{d1}(p) – I_{d2}(p)= [a_{d1}(p) – a_{d2}(p)]*e^{\varphi_d(p)}$$

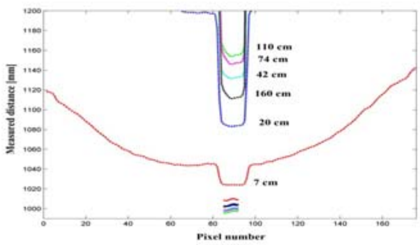
and so $\varphi_d(p)= \arg(I_{m1}(p) – I_{m2}(p))$

For a known k one gets:

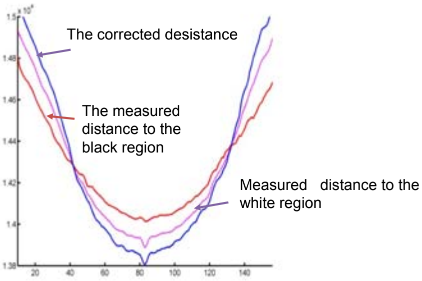
$$I_p(p)=[ I_{m1}(p) – I_{m2}(p)]/(1-k)$$



## Results

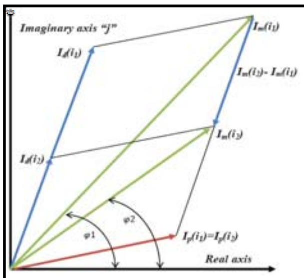



The measured distances in the selected region is plotted with dash lines and the corrected distances to the black square with continuous line

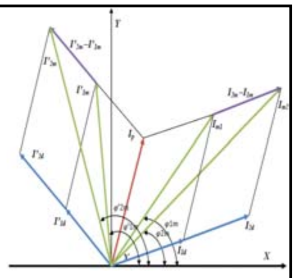



Plot of the measured distances along the black and white vertical lines



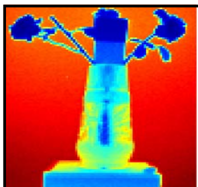



The graphical representation of the measured signals $I_m(i_1)$, $I_p$ and $I_m(i_2) – I_m(i_1)=I_d(i_2) - I_d(i_1)$



The graphical representation of the measured signals $I_{1m}$ and $I_{2m}$ , the perturbation signal $I_p$ and the unperturbed signals $I_{1d}$ and $I_{2d}$. With primes are represented the same signals at the edge of the picture.

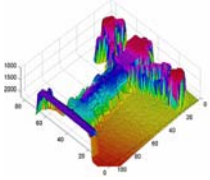




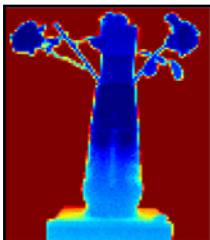
The distance image of the vase, without correction, with distance coded in color

An intensity image of the vase with two labels –white and black- on the top, at the same distance to the camera

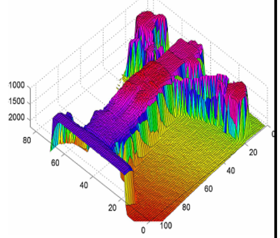
A 3-d plot of the distance image where one can see the big difference (cca. 0,5m) in distance for the two labels (white, black) in the upper part of the vase



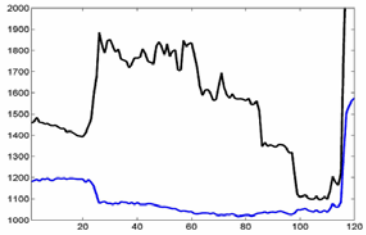




The distance image of the vase, with correction, with distance coded in colour

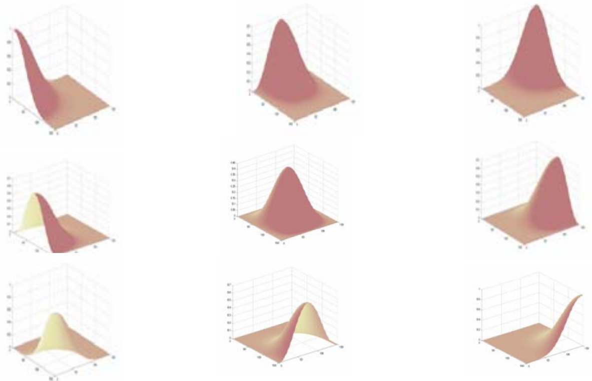


The 3-d plot of the distance image with correction; the two labels now appear at the same distance




The plots of the distances along a vertical line passing in the middle of the vase;
the upper one – before correction;
the bottom one – after correction

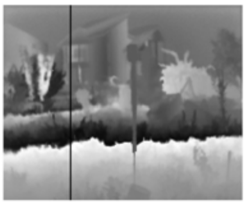




The graphics of membership degrees for *m=3, n=3* and *λ=2*



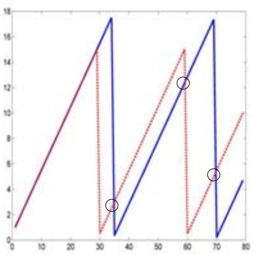
## Further Results



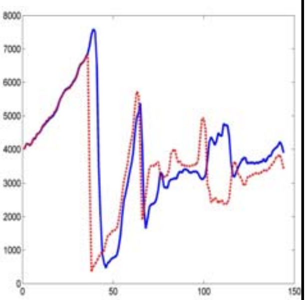
The distance image of the scene, closer objects are black and farther white. The measured distance along the black vertical line is plotted in the next slide for two modulation frequencies.

The logarithm of the amplitude image of the scene





The points where the ambiguity can't be solved are marked with circles. On the abscise axis is represented the distance and on the ordinate the measured distances



The measured distance along a vertical line of the distance image for the two modulation frequencies used

## Applications

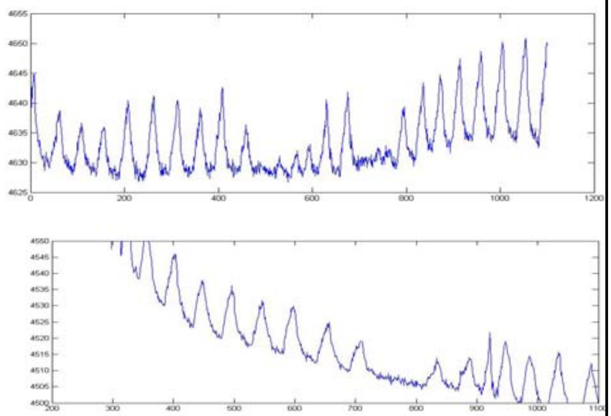
•Action recognition: -surveillance

•Safety in construction (real time detection of slowly moving hand objects)

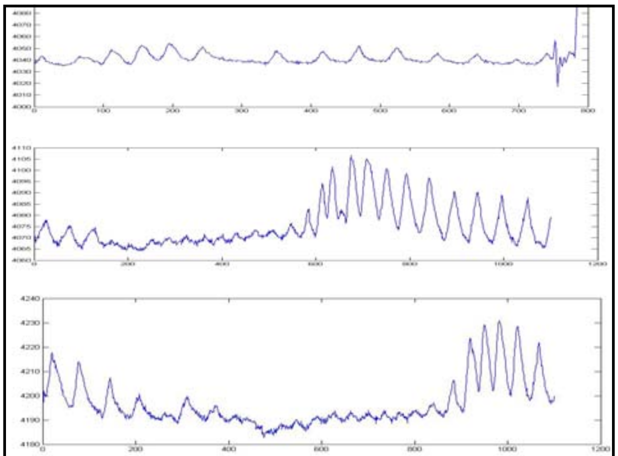
•Automatic human assistance in medical care

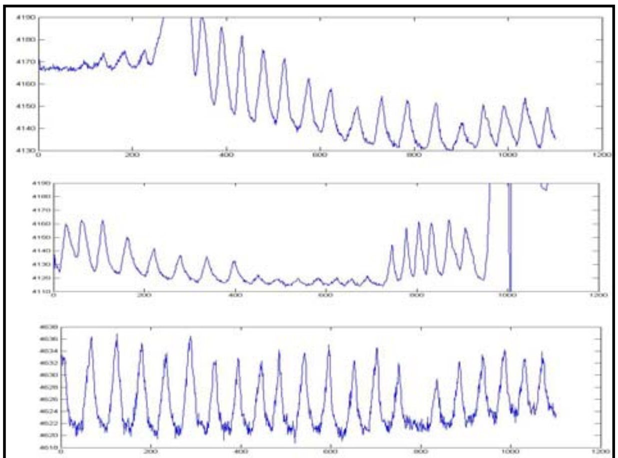
•Main advantage: simple image segmentation











# References


- T. Kahlmann, F. Rmondino, and H. Ingensand. Calibration for increased accuracy of the range imaging camera SwissRanger. In *Image Engineering and vision Metrology(IEVM),* 2006
- R. Lange, 3D Time-OF-Flight Distance Measurement with Custom Solid-StateImage Sensors in CMOS/CCD-Technology, PHD Thesis, University of Siegen, 2000
- H. Rapp, Experimental and theoretical investigation of correlating TOF-camera systems. Master's thesis, University of Heidelberg, Germany, 2007




## The Complex-number model

$$I(i) = a(i)\exp(j\varphi(i)),$$

$$I_m(i) = I_d(i) + I_p(i) = a_d \exp(j\varphi_d(i)) + a_p \exp(j\varphi_p(i)),$$



## The Complex-number model

$$\varphi_d^{'}(i) = \varphi_d(i)$$

$$I_d^{'}(i) - I_d(i) = \left(a_d^{'}(i) - a_d(i)\right)\exp(j\varphi_d(i)) = \Delta\exp(j\varphi_d(i))$$

$$I_p^{'}(i) = I_p(i)$$



## The Complex-number model

$$I_m^{'}(i) = I_d^{'}(i) + I_p^{'}(i) = I_d^{'}(i) + I_p(i)$$

$$I_m^{'}(i) - I_m(i) = I_d^{'}(i) - I_d(i) = \Delta\exp(j\varphi_d(i)).$$

## The Complex-number model

$$I_d(i_1) = I_d(i_2), \qquad \varphi_d(i_1) = \varphi_d(i_2) = \varphi.$$

$$I_m(i_1) - I_m(i_2) = a_d(i_1)\exp(j\varphi) - a_d(i_2)\exp(j\varphi) = [a_d(i_1) - a_d(i_2)]\exp(j\varphi)$$



## The Complex-number model

$$a_d(i_1) = ka_d(i_2).$$

$$I_d(i_1) = kI_d(i_2),$$

$$I_d(i_1) = \frac{k}{k-1}[I_m(i_1) - I_m(i_2)],$$

$$I_p(i_1) = I_p(i_2) = \frac{1}{k-1}[kI_m(i_2) - I_m(i_1)].$$



## The Complex-number model

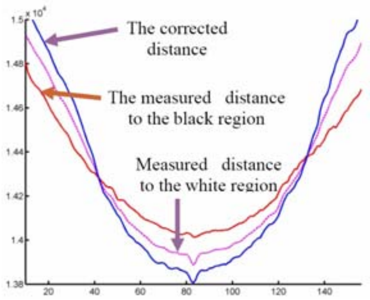



Fig. 1. Plot of the measured distances along the two vertical lines: black line is pictured in red, whereas white line is pictured in magenta.

## The Complex-number model

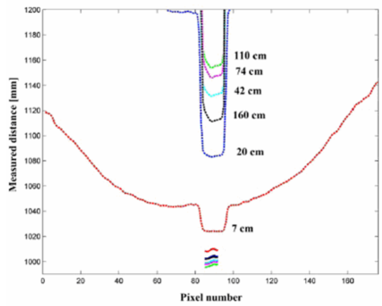



Fig. 2. The measured distances are plotted with dash lines and the corrected distances to the black square with continuous lines.

## The Complex-number model

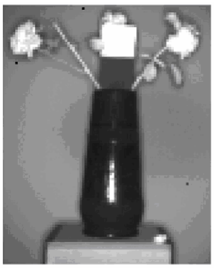


Fig. 3. An intensity image of the vase with two labels –white and black on the top, at the same distance to the camera.

## The Complex-number model

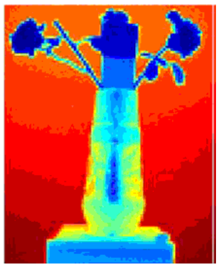


Fig. 4. The distance image of the vase, without correction, with distance coded in color.

## The Complex-number model

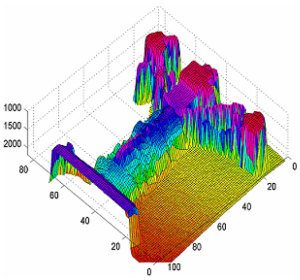



Fig. 5. A 3-d plot of the distance image where one can see the big difference (cca. 0,5m) in distance for the two labels (white, black) in the upper part of the vase.

## The Complex-number model

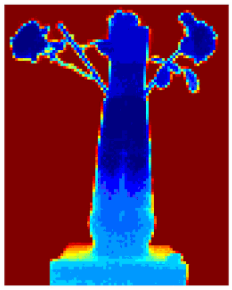


Fig. 6. The distance image of the vase, with correction, with distance coded in colour.

## The Complex-number model

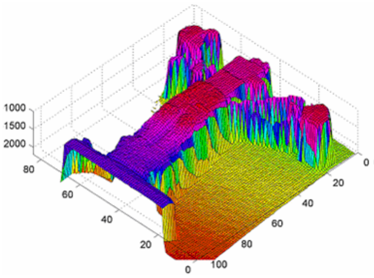



Fig. 7. The 3-d plot of the distance image with correction; the two labelsnow appear at the same distance.

## The Complex-number model

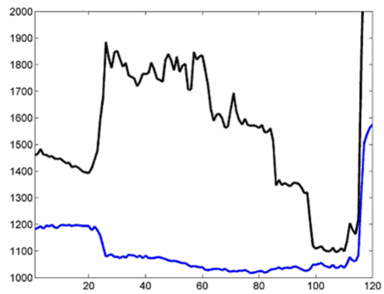



Fig. 8. The plots of the distances along a vertical line passing in the middle of the vase; the upper one - before correction; the bottom one – after correction .