# Sensor Fused Scene Reconstruction and Surface Inspection

***Daniel Thien-An Moodie***

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

**Master of Science**

**In Mechanical Engineering**

**Alfred L. Wicks**

**Kathleen Meehan**

**John P. Bird**

Feb 20, 2014

Blacksburg, Virginia

Keywords:
Sensor Fusion, 3D Scene Reconstruction, Computer Vision, Robotic Perception, Surface Defect Characterization

Permissions table of contents

**Draft 09/01/2009**

(Questions? Concerns? Contact Gail McMillan, Director of the Digital Library and Archives at Virginia Tech's University Libraries: gailmac@vt.edu)

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# Virginia Tech ETD Fair Use Analysis Results

***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 3b.SiCK, "LMS221 outdoor LiDAR specifications," 2013. [Online]. Available: https://www.mysick.com/eCat.aspx?go=FinderSearch&Cat=Gus&At=Fa&Cult=English&FamilyID=344&Category=Produktfinder&Selections=34284,34258. [Accessed: 29-Oct-2013].

Report generated on: 03-06-2014 at : 08:45:42

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***against fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in*

***favor of fair use***

**Draft 09/01/2009**

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# Virginia Tech ETD Fair Use Analysis Results

***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 4a. Zygo, "Optical Profilers - How Optical Profilers Work." [Online]. Available: http://www.zygo.com/?/met/profilers/opticalprofilersabout.htm. [Accessed: 19-Feb-2014].

Report generated on: 04-02-2014 at : 16:15:25

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***against fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

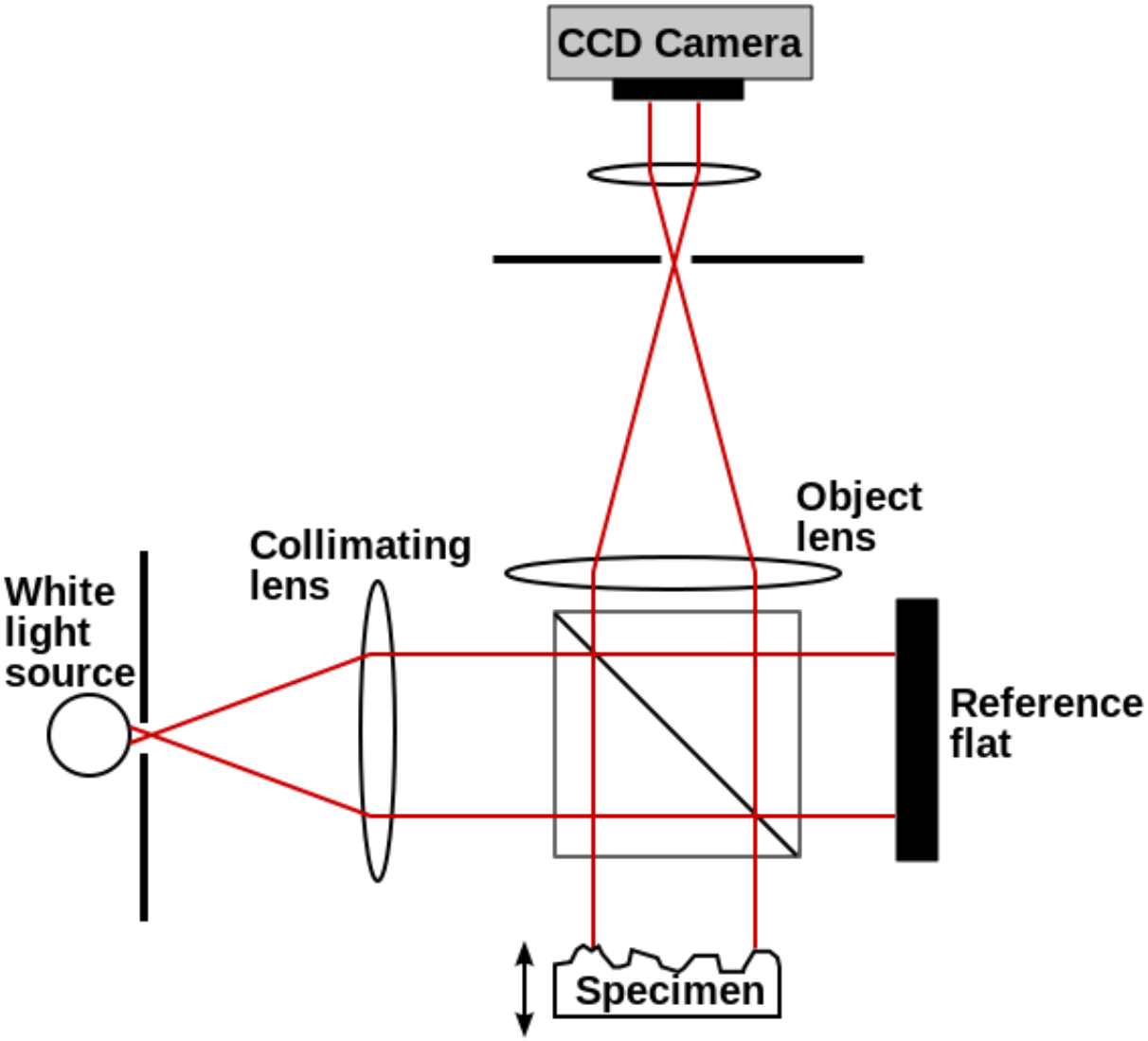
Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


W3C
XHTML
1.0

# File:Twyman-Green interferometer set up as white light scanner.svg

From Wikipedia, the free encyclopedia




Twyman-Green_interferometer_set_up_as_white_light_scanner.svg (SVG file, nominally 570 × 517 pixels, file size: 15 KB)

This image rendered as PNG in other sizes: 200px, 500px, 1000px, 2000px.

This is a file from the Wikimedia Commons. Information from its **description page there** is shown below.
Commons is a freely licensed media file repository. You can help.

## Summary

**Description** **English:** Twyman-Green interferometer set up as a white light scanner

**Date**

**Source** Own drawing, created using Inkscape

**Author** User:Stigmatella aurantiaca

# Licensing



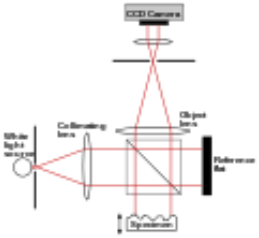
# Original upload log

Transferred from en.wikipedia (http://en.wikipedia.org) to Commons using For the Common Good. The original description page was here (//en.wikipedia.org/w/index.php?title=File:Twyman-Green_interferometer_set_up_as_white_light_scanner.svg). All following user names refer to en.wikipedia.

| Date/Time | Dimensions | User | Comment |
|---|---|---|---|
| 18:30, 17 June 2012 | 570 × 517 (14,932 bytes) | w:en:Stigmatella aurantiaca (talk \| contribs) | Deleted an unused layer that was bloating the file size. |
| 09:08, 17 June 2012 | 570 × 517 (373,021 bytes) | w:en:Stigmatella aurantiaca (talk \| contribs) | Description: Twyman-Green interferometer set up as a white light scanner Author: [[User:Stigmatella aurantiaca]] Source: Own drawing, created using Inkscape {{cc-by-sa-3.0}} {{GFDL-self}} |

# File history

Click on a date/time to view the file as it appeared at that time.

| | Date/Time | Thumbnail | Dimensions | User | Comment |
|---|---|---|---|---|---|
| current | 09:36, 14 December 2013 |  | 570 × 517 (15 KB) | Stigmatella aurantiaca | Transferred from en.wikipedia: see original upload log above |

# File usage

The following pages on the English Wikipedia link to this file (pages on other projects are not listed):

- Interferometry
- White light scanner
- User:Stigmatella aurantiaca

# Metadata

This file contains additional information, probably added from the digital camera or scanner used to create or digitize it. If the file has been modified from its original state, some details may not fully reflect the modified file.

| | |
|---|---|
| **Width** | 570 |
| **Height** | 517 |

Retrieved from "http://en.wikipedia.org/wiki/File:Twyman-Green_interferometer_set_up_as_white_light_scanner.svg"

**Draft 09/01/2009**

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# Virginia Tech ETD Fair Use Analysis Results

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Name: Daniel Moodie

Description of item under review for fair use: Figure 5a. C. Caraffi, S. Cattani, and P. Grisleri, "Off-Road Path and Obstacle Detection Using Decision Networks and Stereo Vision," IEEE Trans. Intell. Transp. Syst., vol. 8, 2007.

Report generated on: 02-26-2014 at : 14:57:30

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


W3C
XHTML
1.0

**Draft 09/01/2009**

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# Virginia Tech ETD Fair Use Analysis Results

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Name: Daniel Moodie

Description of item under review for fair use: Figure 5b. R. Szeliski, Computer vision: algorithms and applications, 1st ed. Springer, 2011, p. 979.

Report generated on: 02-26-2014 at : 14:59:18

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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Name: Daniel Moodie

Description of item under review for fair use: Figure 6. P. Favaro, "Depth from focus/defocus," 2002. [Online]. Available: http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/FAVARO1/dfdtutorial.html. [Accessed: 07-Nov-2013].

Report generated on: 02-26-2014 at : 15:01:04

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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# Virginia Tech ETD Fair Use Analysis Results

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Name: Daniel Moodie

Description of item under review for fair use: Figure 7. D. Lanman and G. Taubin, "Build your own 3D scanner: optical triangulation for beginners," SIGGRAPH ASIA 09 ACM SIGGRAPH ASIA 2009 Courses, pp. 1–94, 2009.

Report generated on: 02-26-2014 at : 15:05:26

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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**Draft 09/01/2009**

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***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 9a. C. Guestrin, "Support Vector Machines," 2005. [Online]. Available: http://www.cs.cmu.edu/~guestrin/Class/10701-S06/Slides/svms-s06.pdf. [Accessed: 26-Feb-2014].

Report generated on: 02-26-2014 at : 15:10:01

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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**Draft 09/01/2009**

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***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 9b. StatSoft, "Support Vector Machines (SVM)." [Online]. Available: http://www.statsoft.com/textbook/support-vector-machines. [Accessed: 21-Nov-2013].

Report generated on: 02-26-2014 at : 15:10:52

## Based on the information you provided:

## Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

## Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

## Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

## Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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Name: Daniel Moodie

Description of item under review for fair use: Figure 13a. D. Lanman and G. Taubin, "Build Your Own 3D Scanner : 3D Photography for Beginners," Siggraph, 2009.

Report generated on: 02-26-2014 at : 15:12:25

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

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Name: Daniel Moodie

Description of item under review for fair use: Figure 13b. "Temporal Dithering of Illumination for Fast Active Vision." [Online]. Available: http://staff.aist.go.jp/shun-yamazaki/research/dlp/.

Report generated on: 02-26-2014 at : 15:13:09

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


W3C
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**Draft 09/01/2009**

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# Virginia Tech ETD Fair Use Analysis Results

***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 13c. D. Hoiem, "How the Kinect Works Kinect Device," Computational Photography, 2010. [Online]. Available: http://courses.engr.illinois.edu/cs498dh/fa2011/lectures/Lecture 25 - How the Kinect Works - CP Fall 2011.pdf.

Report generated on: 02-26-2014 at : 15:14:54

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


W3C
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1.0

**Draft 09/01/2009**

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***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 14. Y. A. Barak Freedman, Alexander Shpunt, "Distance-Varying Illumination and Imaging Techniques for Depth Mapping," US20100290698 A118-Nov-2010.

Report generated on: 02-26-2014 at : 15:21:20

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

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Name: Daniel Moodie

Description of item under review for fair use: Figure 15. G. B. S. D. A. Murguet, "MonoSLAM," 2012. [Online]. Available: http://www.ensta-paristech.fr/~filliat/Courses/2011_projets_C10-2/BRUNEAU_DUBRAY_MURGUET/monoSLAM_bruneau_dubray_murguet_en.html. [Accessed: 19-Feb-2014].

Report generated on: 02-26-2014 at : 15:36:44

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

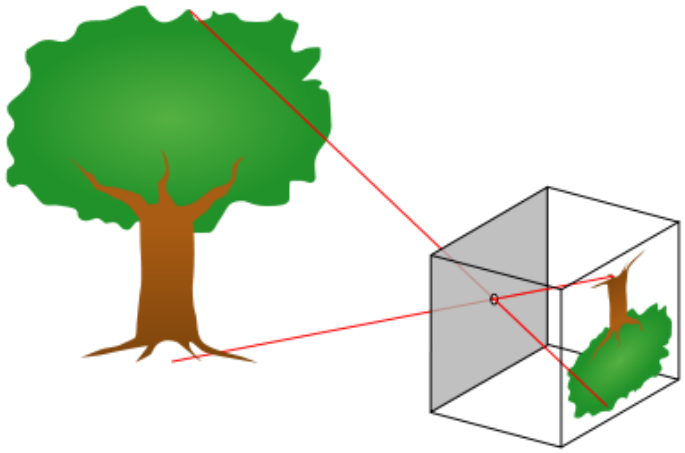
Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


W3C
XHTML
1.0

# File:Pinhole-camera.svg

From Wikipedia, the free encyclopedia



Pinhole-camera.svg (SVG file, nominally 400 × 273 pixels, file size: 25 KB)

This image rendered as PNG in other sizes: 200px, 500px, 1000px, 2000px.

This is a file from the Wikimedia Commons. Information from its **description page there** is shown below.
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## Summary

Template:Information ;0

## Licensing:

I, the copyright holder of this work, release this work into the **public domain**. This applies worldwide.
In some countries this may not be legally possible; if so:
*I grant anyone the right to use this work **for any purpose**, without any conditions, unless such conditions are required by law.*

## File history

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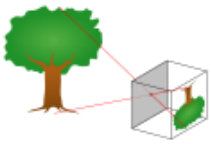
| | Date/Time | Thumbnail | Dimensions | User | Comment |
|---|---|---|---|---|---|
| current | 04:19, 24 May 2008 |  | 400 × 273 (25 KB) | Pbroks13 | {{Information |Description=SVG redraw of Image:Pinhole-camera.png |Source=http://commons.wikimedia.org/wiki/Image:Pinhole-camera.png |Date=2008-05-23 |Author=en:User:DrBob (original); en:User:Pbroks13 |Permission= |other_versions= }} |

## File usage

The following pages on the English Wikipedia link to this file (pages on other projects are not listed):

- Camera
- Camera lens
- Motion analysis
- Pinhole camera
- Pinhole camera model
- Talk:Camera lens/Archive 1
- User:Pbroks13/Gallery/Redrawn
- User talk:DrBob
- User talk:Pbroks13/Archive 2009

# Global file usage

The following other wikis use this file:

- Usage on ar.wikipedia.org
  - كاميرا ذات الثقب
- Usage on az.wikipedia.org
  - Pinhol kamera
- Usage on bg.wikipedia.org
  - Стенопеична фотография
  - Стенопеичен фотоапарат
  - Шаблон:Mosaic row generator
  - Шаблон:Mosaic row generator/doc
- Usage on cs.wikipedia.org
  - Objektiv
- Usage on en.wikibooks.org
  - Adventist Youth Honors Answer Book/Arts and Crafts/Photography
  - Adventist Youth Honors Answer Book/Arts and Crafts/Digital Photography
  - Wikijunior:How Things Work/Camera
- Usage on es.wikipedia.org
  - Cámara estenopeica
- Usage on fa.wikipedia.org
  - دوربین سوراخ‌سوزنی
  - عکاسی
  - لنز دوربین عکاسی
- Usage on fr.wikibooks.org
  - Photographie/Les premiers pas/L'appareil photographique
- Usage on id.wikipedia.org
  - Pengguna:Bennylin/Mosaik
  - Pengguna:Mikhailov Kusserow/Mosaik
  - Pengguna:Kenrick95/Mosaik
  - Templat:Wikimedia logo mosaic
- Usage on it.wikipedia.org
  - Camera oscura
  - Stenoscopia
- Usage on ko.wikipedia.org
  - 사진술
- Usage on ms.wikipedia.org
  - Senarai reka cipta China
  - Kanta fotografi
- Usage on nl.wikipedia.org
  - Gebruiker:Sitethief/Lijst van Chinese uitvindingen
- Usage on pl.wikibooks.org
  - Fotografia/Obiektywy

    - Fotografia/Wersja do druku
- Usage on pt.wikipedia.org
    - Câmera pinhole
- Usage on ru.wikipedia.org
    - Список изобретений, сделанных в Китае
- Usage on simple.wikipedia.org
    - Camera obscura
    - Pinhole camera
- Usage on sv.wikipedia.org
    - Fotografi
    - Hålkamera
- Usage on ta.wikipedia.org
    - ஊசித்துளை காமரா
- Usage on te.wikipedia.org
    - కెమెరా కటకం
- Usage on tr.wikipedia.org
    - Lens (fotoğrafik)
    - İğne deliği kamera
- Usage on zh.wikipedia.org
    - 針孔相機
    - User:Zanhsieh/沙盒
    - 中国先秦发明列表

# Metadata

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| | |
|---|---|
| **Width** | 400 |
| **Height** | 273 |

Retrieved from "http://en.wikipedia.org/wiki/File:Pinhole-camera.svg"

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Name: Daniel Moodie

Description of item under review for fair use: Figure 17b. D. Lanman and G. Taubin, "Build Your Own 3D Scanner : 3D Photography for Beginners," Siggraph, 2009.

Report generated on: 02-26-2014 at : 15:40:34

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

### Factor 4

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Name: Daniel Moodie

Description of item under review for fair use: Figure 18. K. Konolige, J. Augenbraun, N. Donaldson, C. Fiebig, and P. Shah, "A low-cost laser distance sensor," 2008 IEEE Int. Conf. Robot. Autom., pp. 3002–3008, May 2008.

Report generated on: 02-26-2014 at : 15:41:40

## Based on the information you provided:

### Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

### Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

### Factor 3

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**Draft 09/01/2009**

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# Virginia Tech ETD Fair Use Analysis Results

***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: Figure 19. D. Lanman and G. Taubin, "Build Your Own 3D Scanner : 3D Photography for Beginners," Siggraph, 2009.

Report generated on: 02-26-2014 at : 15:41:08

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### Factor 2

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### Factor 3

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### Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

## Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*


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# Documentation

# Using Kinfu Large Scale to generate a textured mesh

This tutorial demonstrates how to use KinFu Large Scale to produce a mesh (in meters) from a room, and apply texture information in post-processing for a more appealing visual result. The first part of this tutorial shows how to obtain the TSDF cloud from KinFu Large Scale. The second part shows how to convert the TSDF cloud into a uniform mesh. The third part shows how to texture the obtained mesh using the RGB images and poses we obtained from KinFu Large Scale.

# Part 1: Running pcl_kinfu_largeScale to obtain a TSDF cloud

*TSDF Cloud*

This section describes the TSDF Cloud, which is the expected output of KinFu Large Scale. A TSDF cloud looks like the one in the following video.

You may be wondering: *"What is the difference between a TSDF cloud and a normal point cloud?"* Well, a TSDF cloud *is* a point cloud. However, the TSDF cloud makes use of how the data is stored within GPU at KinFu runtime.

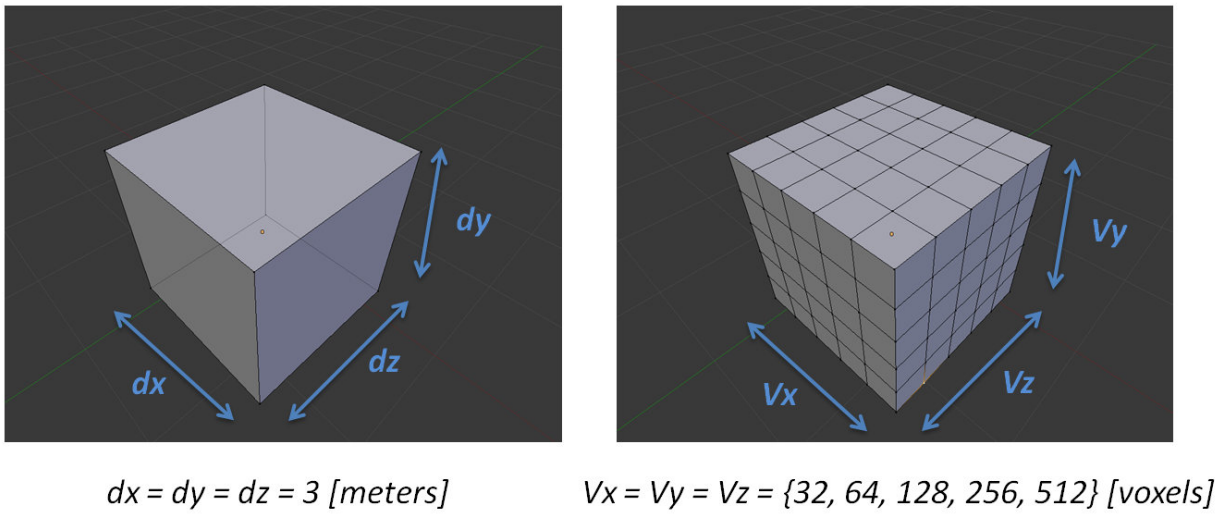


*Figure 1: The cube is subdivided into a set of Voxels. These voxels are equal in size. The default size in meters for the cube is 3 meters per axis. The default voxel size is 512 per axis. Both the number of voxels and the size in meters give the amount of detail of our model.*

As you may already know, the way in which the TSDF volume is stored in GPU is a voxel grid. KinFu subdivides the physical space of the cube (e.g. 3 meters) into a voxel grid with a certain number of voxels per axis (say, 512 voxels per axis). The size in meters of the cube and the number of voxels give us the resolution of our cube. The quality of the model is proportional to these two parameters. However, modifying them affects directly the memory footprint for our TSDF volume in GPU. Further information on these properties can be found in the relevant papers.

At the time of data extraction, the grid is traversed from front to back, and the TSDF values are checked for each voxel. In the figure below, you may notice that the values range from -1 to 1.

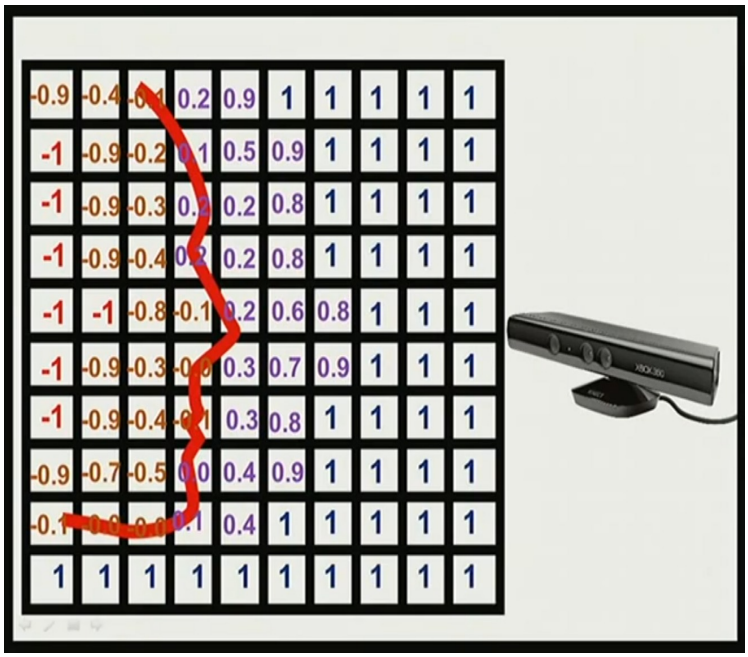

*Figure 2: A representation of the TSDF Volume grid in the GPU. Each element in the grid represents a voxel, and the value inside it represents the TSDF value. The TSDF value is the distance to the nearest isosurface. The TSDF has a positive value whenever we are "in front" of the surface, whereas it has a negative value when inside the isosurface. At the time of extraction, we avoid extracting the voxels with a value of 1, since they represent empty space, and are therefore of no use to our model.*

Since we want to minimize the required bandwidth between GPU and CPU, we will only extract the voxels with a TSDF value in the range [-1, 0.98]. We avoid extracting voxels with a value of 1 because they represent empty space. In this way we ensure that we only extract those voxels that are close to the isosurface. The TSDF cloud is not in meters. The X,Y,Z coordinates for each of the extracted points correspond to the voxel indices with respect to the world model.

As mentioned above, the TSDF cloud is a section of the TSDF volume grid; which is why the points are equally-spaced and uniformly-distributed. This can be observed when we zoom in the point cloud.

*Running pcl_kinfu_largeScale*

Finally, we are ready to start KinFu Large Scale. After building the git master, we will call the application:

```
$ ./bin/pcl_kinfu_largeScale -r -et
```

The *-r* parameter enables registration, which is used for texture extraction. In particular, it allows us to extract the correct focal length. The *-et* parameter enables the texture extraction. By enabling this option, we will extract RGB images at the same time that we are scanning. All the RGB snapshots are saved in the KinFuSnapshots folder. Each RGB image will be saved with its corresponding camera pose. It is suggested to empty this directory before starting the scan, in this way we avoid using textures that do not correspond to our latest scan.

The video below shows the process of scanning a large area. Notice the smooth movements at the time of scanning. Furthermore, notice how a complex object (e.g. chair) is kept within sight at the time of shifting so that tracking does not get lost.

- The shifting can be triggered by rotation or translation.
- Every time we shift out part of the cube, four main things happen: 1)We save the data in the slice that is shifted out and send it to the world model, which is stored in CPU. 2) We clear that slice to allow for new data to be added. 3) We shift the cube's origin. 4) We retrieve existing data (if any) from the world model and load it to the TSDF volume. This is only present when we return to areas that we previously scanned.
- Whenever we are satisfied with the area that we have scanned, we press the "L" key to let KinFu know that we are ready to perform the exit routine. However, the routine is not executed until we shift again.

What the exit routine will do is to get all the information regarding our model, comprise it in a point cloud and save it to disk as *world.pcd* The PCD file is saved in the same directory from where we run KinFu Large Scale.

Since we used the *-et* option, you will also find a folder called KinFuSnapshots, which contains all the RGB images and its corresponding poses for this scan. The following video demonstrates the scanning process and the generated output:

The next part of this tutorial will demonstrate how to get a mesh from the TSDF cloud.

# Part 2: Running pcl_kinfu_largeScale_mesh_output to convert the TSDF cloud into a mesh

This section describes how to convert the TSDF Cloud, which is the expected output of KinFu Large Scale, into a mesh. For this purpose we will use the meshing application in KinFu Large Scale. The input for this application is the world model as a PCD file. The output is a set of meshes, since the world model is processed as a set of cubes.

The reason why we load the world model in cubes is because we have the limitation of memory in the GPU. A point of improvement for the meshing application could be to return the complete mesh instead of a set of meshes. Contributions welcome!

After we obtain a set of meshes, we process them in Meshlab in order to merge them as a single mesh. At this point it is important to mention that we need to save the mesh as a ply file without binary encoding.

The mesh is also simplified using quadric edge decimation. The reason for doing this is to reduce the time it takes to perform the UV mapping in the next step. The UV mapping is done for each face in the mesh. Therefore, by reducing the number of faces we reduce the time it takes to generate the texture.

We run this application with the command:

```
$ ./bin/pcl_kinfu_largeScale_mesh_output world.pcd
```

where *world.pcd* is the world model we obtained from KinFu Large Scale. The following video shows the process of creating, merging, and simplifying the meshes into a single mesh which we will use for texturing.

The next part of this tutorial will demonstrate how to generate the texture for the mesh we have just created.

# Part 3: Running pcl_kinfu_largeScale_texture_output to generate the texture

This section describes how to generate the textures for the mesh we created in the previous step. The input for this application is the merged mesh, as well as the RGB captures and poses we saved during the scanning in part 1. The RGB captures and poses should be in the KinFuSnapshots folder. We select the most representative snapshots for the sake of time. Each snapshot must have its corresponding camera pose in a text file in the same folder.

The generated PLY mesh must be in the same folder as the snapshots and camera poses. The output will be generated as an OBJ file with its corresponding MTL file. The former contains data about the mesh, whereas the latter contains information about the texture. Unfortunately at this point some of the generated textures may seen patched, this is based on how the RGB camera in the Kinect adapts to light. A potential area of improvement could be to equalize the color tones in the images. Contributions welcome!

In order to run the texturing application, we use the following command:

```
$ ./bin/pcl_kinfu_largeScale_texture_output path/to/merged_mesh.ply
```

The following video shows the process in detail. It also shows the final output for this tutorial.

# Output

The viewer below displays a sample of the output obtained after the entire pipeline. The mesh was decimated, and the faces were removed so that only the points remained. So, the output mesh was converted from mesh (.ply) to point cloud (.pcd) to show it in this tutorial. The vertex count is ~900k points.

To further demonstrate the capabilities of KinFu Large Scale, we made another example with a room.

# General Recommendations

There is a set of recommendations that we want to mention regarding the use of KinFu Large Scale. These recommendations are listed below:

1. **Scan scenes with enough details for ICP:** It is a known fact that ICP does not perform well in scenes with few details, or where there are a lot of co-planer surfaces. In other words, if the only thing you have is a wall and floor, most probably the tracking will not perform well.
2. **Frame rate is less than original KinFu:** The code in Kinfu largescale is experimental. There are still many areas in which the performance can be optimized to provide a faster execution. In our tests, the obtained frame rate is around 20 fps. We are using a GTX480 and 4GB of RAM. The decrease in frame rate is mainly because of two things. First, that the code has not yet been completely optimized. Second, that additional operations are taking place in the frame processing loop as a result of the large scale implementation.
3. **Scan smoothly:** Since there are more things happening per frame, KinFu Large Scale may not respond as fast as the original KinFu. Data is exchanged between GPU and CPU especially at the time of shifting. Performing smooth movements, in particular at the time of shifting, decreases the risk of losing the camera pose tracking. Be patient and you will get good results.

# Related Executables

There are three executables related to this tutorial:

- **pcl_kinfu_largeScale:** In charge of obtaining the scan of the room. Its functionality is almost the same as KinFu, except that it includes the capability of shifting the cube that is being scanned to allow for large area 3D reconstruction. The output from this application is the world reconstructed model as a TSDF cloud. The concept of TSDF cloud will be explained better below. Another output from this application is a set of RGB screenshots and their corresponding camera poses.
- **pcl_kinfu_largeScale_mesh_output:** This application is in charge of generating a set of meshes from the extracted TSDF

world cloud. The TSDF world model is processed as cubes of points and generates a mesh for each of these cubes.

- As an additional processing step, the current state of the implementation requires that the output meshes are merged in the software of your preference. In other words, the output of the meshing application is given as a set of mesh cubes. This tutorial has been done using with Meshlab (*merge visible layers* function in Meshlab). Since the following step is performed on a per-face basis, it is also optional to decimate the mesh in order to decrease the time it takes to generate the texture.
- **pcl_kinfu_largeScale_texture_output:** After the meshes are generated and merged into one, this application is in charge of using the RGB screenshots and their corresponding camera poses taken during the scan to perform UV mapping in order to reconstruct the texture of the model.

# Conclusion

In this tutorial we have shown the pipeline from scanning to final texturing using KinFu Large Scale. The - *experimental* - code is available in the master branch of PCL.

**Draft 09/01/2009**

(Questions? Concerns? Contact Gail McMillan, Director of the Digital Library and Archives at Virginia Tech's University Libraries: gailmac@vt.edu)

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# Virginia Tech ETD Fair Use Analysis Results

***This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.***

Name: Daniel Moodie

Description of item under review for fair use: D. Girardeau-Montaut, "Distances Computation - CloudCompareWiki," Cloud Compare Documentation, 2012. [Online]. Available: Figure 39. http://www.danielgm.net/cc/doc/wiki/index.php5?title=Distances_Computation. [Accessed: 26-Feb-2014].

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# AW: Pictures of robots for thesis

M.Hitzel [M.Hitzel@inspectorsystems.de]

**Sent:** Wednesday, February 26, 2014 1:24 AM
**To:** Moodie, Daniel

You can do it when you are mentioning our company name INSPECTOR SYSTEMS together with the pictures.

--
Dipl. Ing. Marcus Hitzel / Managing Director
INSPECTOR SYSTEMS GmbH
Joh. Friedr. Böttgerstr. 19
63322 Rödermark
Germany

fon: +49 (0) 6074 / 917 123-4
fax: +49 (0) 6074 / 917 123-9
e-mail: m.hitzel@inspectorsystems.de
internet: www.inspectorsystems.de

Geschäftsführer: Rainer & Marcus Hitzel
Amtsgericht Offenbach HRB 31526

-----Ursprüngliche Nachricht-----
Von: Moodie, Daniel [mailto:dmoodie@vt.edu]
Gesendet: Dienstag, 25. Februar 2014 18:36
An: info@inspectorsystems.de
Betreff: Pictures of robots for thesis

Hello,
I am currently working on my masters thesis and I would like to use some pictures from your website to discuss current state of the art technologies. All I would need to do this is for you to reply to this email stating that I am allowed to use pictures from your website in my thesis.

Thank you for your time,
Daniel Moodie

# Creaform products' pictures to include in your thesis

Émilie Grenier [emilie.grenier@creaform3d.com]

**Sent:** Friday, February 28, 2014 1:51 PM
**To:** Moodie, Daniel

Hi Daniel,

I received your message (see below) and want to inform you that you have our permission to use our products pictures in your thesis.

Of course, we would like to see the final project before you submit it!

Good luck!

---

Hello,
For my masters thesis I would like to include product photos of your hand held optical CMM. With your written permission, I will include photos and discussion in my thesis.
Thank you for your time,
Daniel Moodie

**ÉMILIE GRENIER**
Regional Marketing Manager, Americas | Responsable régionale du marketing, Amériques

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Daniel Moodie <dmoodie@vt.edu>

# FW: my contact

**Dan Moodie** <Dan.Moodie@ccam-va.com> Wed, Apr 2, 2014 at 4:17 PM
To: "dmoodie@vt.edu" <dmoodie@vt.edu>

**From:** Glenn Hennin [mailto:ghennin@lmi3d.com]
**Sent:** Friday, March 07, 2014 9:48 AM
**To:** Dan Moodie
**Subject:** RE: my contact

Hi Dan

Sorry for the delay but here is the diagram that you what to use in your these and if you do mentioned pricing the retail cost of the Gocator 2342 sensor is $10,000 USD

Please send me a copy of the thesis when complete

Thanks

**Glenn Hennin**
Business Development Manager

+1 519 737 6377 **Main**
+1 519 984 1358 **Mobile**
+1 519 737 0599 **Fax**

www.lmi3D.com

CANADA EAST: 2160 Fasan Drive, Oldcastle, Ontario, Canada N0R 1G0



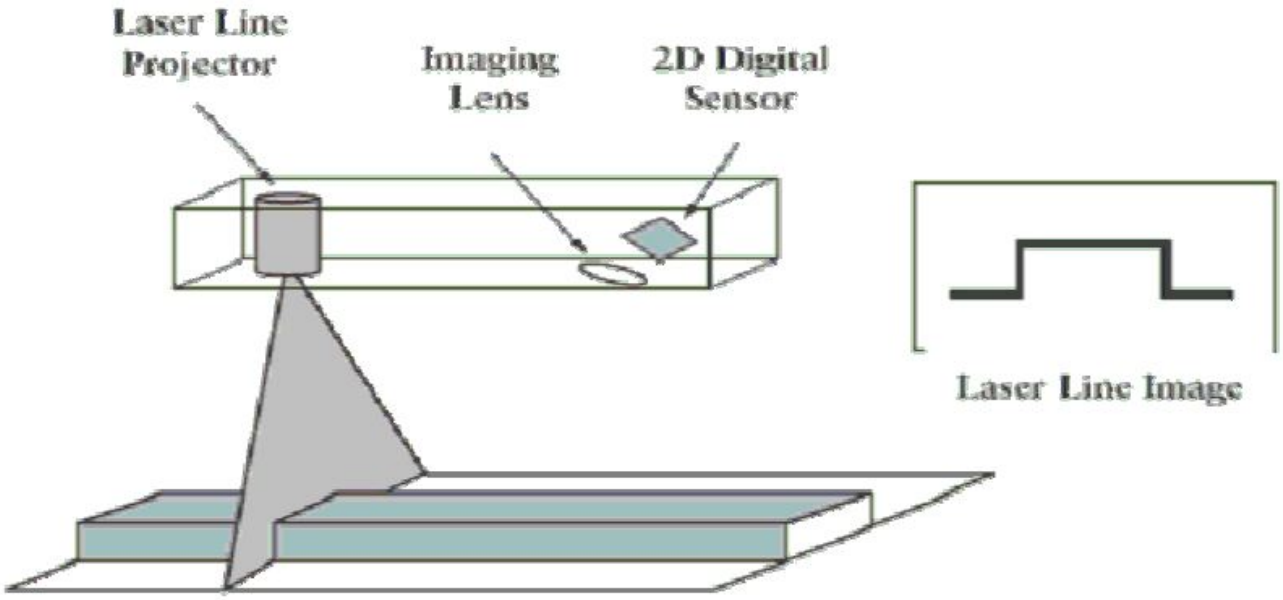
**From:** Dan Moodie [mailto:Dan.Moodie@ccam-va.com]
**Sent:** Monday, March 03, 2014 9:06 AM
**To:** Glenn Hennin
**Subject:** RE: my contact

Hello Glen,

Thank you for this information. I think I will discuss the Gocator 2342 in my thesis. Can you give me an estimate on buying just one sensor so I can put a price in?

Also this is one of the images from the RoLine user manual that I wanted to use because it was a good figure on how profilometers work

Also this is one of the images from the RoLine user manual that I wanted to use because it was a good figure on how profilometers work.




---

**From:** Glenn Hennin [ghennin@lmi3d.com]
**Sent:** Thursday, February 27, 2014 8:59 AM
**To:** Dan Moodie
**Subject:** RE: my contact

Hi Dan

The attached file is the new Roline sensor as mentioned and if you can refer to this as the latest (newest) Roline sensor it would be great

And again the new sensor name is Gocator 2342 model

**Glenn Hennin**
Business Development Manager

+1 519 737 6377 **Main**
+1 519 984 1358 **Mobile**
+1 519 737 0599 **Fax**

www.lmi3D.com

CANADA EAST: 2160 Fasan Drive, Oldcastle, Ontario, Canada N0R 1G0

---



---

**From:** Glenn Hennin [mailto:ghennin@lmi3d.com]

**From:** Glenn Hennin [mailto:ghennin@lmi3d.com]
**Sent:** Thursday, February 27, 2014 11:18 AM
**To:** 'dan.moodie@ccam-va.com'
**Subject:** my contact

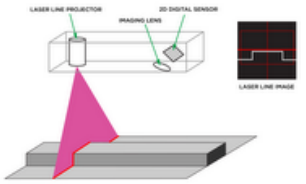
**Glenn Hennin**
Business Development Manager

+1 519 737 6377 **Main**
+1 519 984 1358 **Mobile**
+1 519 737 0599 **Fax**

www.lmi3D.com

CANADA EAST: 2160 Fasan Drive, Oldcastle, Ontario, Canada N0R 1G0






**IMAGE_Laser-Line-Operation.png**
103K

Daniel Moodie <dtmoodie@gmail.com>

# FW: MESA / photographs

**Dan Moodie** <Dan.Moodie@ccam-va.com> Mon, Mar 3, 2014 at 8:31 AM
To: "dtmoodie@gmail.com" <dtmoodie@gmail.com>

---

From: Gerald Dahlmann [Gerald.Dahlmann@mesa-imaging.ch]
Sent: Monday, March 03, 2014 2:00 AM
To: Dan Moodie
Subject: MESA / photographs

Hello Daniel,

please feel free to use the product photographs from our website.

Best regards,
Gerald

---

Gerald Dahlmann
Sales

MESA Imaging / Technoparkstrasse 1 / CH-8005 Zürich / Switzerland

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+41 (0)79 551 11 58 (mobile)

-----Ursprüngliche Nachricht-----
Von: contactform@mesa-imaging.ch [mailto:contactform@mesa-imaging.ch]
Gesendet: Mittwoch, 26. Februar 2014 16:48
An: Gerald Dahlmann
Betreff: [Moodie Daniel] SwissRanger Customer request ...

---
Commonwealth Center for Advanced Manufacturing Digital Controls Engineer Daniel Moodie

Virginia
United States
---
Title : Digital Controls Engineer
Firstname : Daniel
Name : Moodie

Company : Commonwealth Center for Advanced Manufacturing
E-Mail : dan.moodie@ccam-va.com
Phone : 7578103485
Principal activity : Programmer
Field of application : Manufacturing
---
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City :
Country : United States
State : Virginia
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Please reply in an email if you will allow me to include a picture of your product from your product page.
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Gmail by Google

Daniel Moodie <dtmoodie@gmail.com>

# FW: Mitutoyo Information

**Dan Moodie** <Dan.Moodie@ccam-va.com> Mon, Mar 3, 2014 at 3:42 PM
To: "dtmoodie@gmail.com" <dtmoodie@gmail.com>

---

**From:** Todd Himes [Todd.Himes@mitutoyo.com]
**Sent:** Monday, March 03, 2014 12:33 PM
**To:** Dan Moodie
**Cc:** George Gosnell
**Subject:** Mitutoyo Information

Dan,

Hope all is well.

I understand from George Gosnell you would like picture permission for your thesis.

Anything you find on the website is considered public domain and can be used for your thesis. If you would like to use pictures from the actual software or measurements on the machine we would like to review prior to usage.

Please let me know if you have any questions.

Have a great day and Best wishes.

Todd Himes

11515 Vanstory Drive, Suite 150

Huntersville, NC 28078

Regional Sales Manager

Cell 704-918-0358

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# Re: Roline

Z Wang [zw@vt.edu]

**Sent:** Tuesday, February 25, 2014 9:22 AM
**To:** Moodie, Daniel

You (Daniel Moodie) have permission to use the previous 2 and any following photos I may provide of the Roline lasers for your thesis.

Z

--
Zhuosong Wang
757.726.7268

On Tue, Feb 25, 2014 at 9:21 AM, Z Wang <zw@vt.edu> wrote:

> 2 attached. Feel free to use the photos.

Connected to Microsoft Exchange

## Dan Moodie

**From:** LUTHER David <David.Luther@hexagonmetrology.com>
**Sent:** Saturday, February 22, 2014 10:38 AM
**To:** Dan Moodie
**Subject:** Romer Arm

Dan

Thank younger your inquiry. You can use any photo from our website or the internet. If these do not work please let me know. I word be interested to know what your thesis was dine on.

Thank you
David Luther

WWW.hexagonmetrology.us