Sensors and Sensing
3D Range Sensing

Todor Stoyanov

Centre for Applied Autonomous Sensor Systems
Örebro University
Sweden

Outline

Outline

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

Basic Principle of Operation

- 3D laser scanners are usually time-of-flight laser sensors.
- The basic principle involved is similar to 2D lidars — sweep a laser beam through the environment.
- The main challenge is to cover a 3D sweep pattern efficiently.
- Important design considerations:
  - Number of moving parts and complexity of optics.
  - Number of laser beam emitters and detectors.
  - Scanning time.

2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).

2D Laser + Actuator

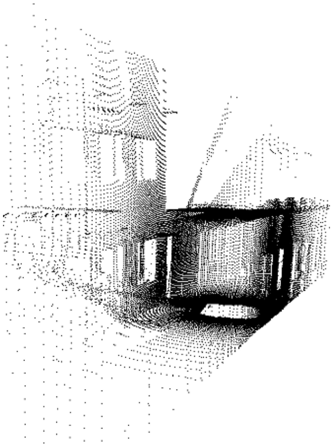
- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).

2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).

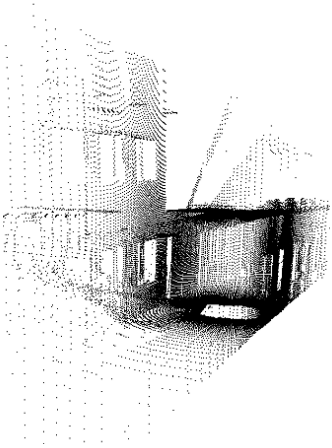
2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).



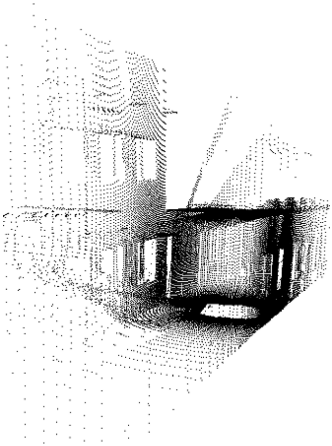
2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).



2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).

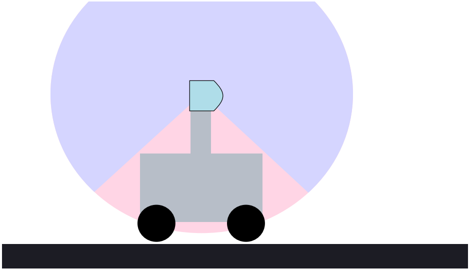


2D Laser + Actuator

- The poor-man's 3D laser scanner
- Use a commercial 2D laser scanner and an actuating unit.
- The actuator can be a servo system, or a stepper-motor based pan-tilt unit.
- For each slice of the 2D laser data, estimate the pose of the laser center H
- Transform 2D points by H.
- For higher precision, estimate H for each laser beam separately.
- Update rate depends on actuator speed (0.5-1Hz is common).

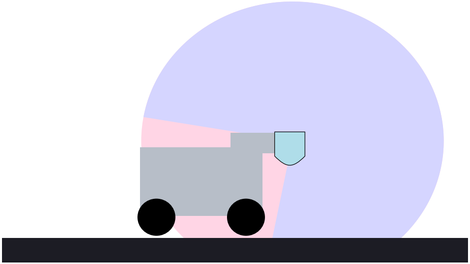
Mounting considerations

- Several possible configurations for the setup: pan-tilt or continuous rotation.
- Mounting configuration on the robot depends on application.



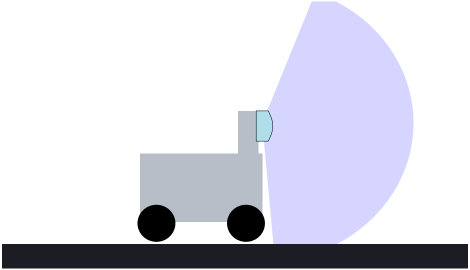
Mounting considerations

- Several possible configurations for the setup: pan-tilt or continuous rotation.
- Mounting configuration on the robot depends on application.



Mounting considerations

- Several possible configurations for the setup: pan-tilt or continuous rotation.
- Mounting configuration on the robot depends on application.

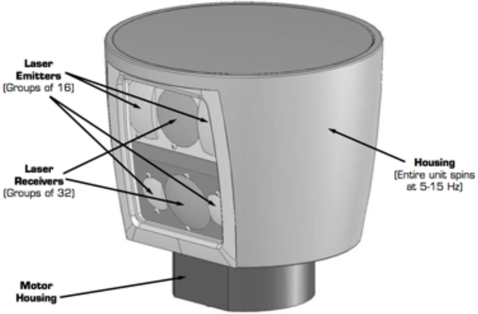


Velodyne Lidars

- Velodyne Lidars are made for automotive applications and deliver directly 3D point clouds.

Velodyne Lidars

Velodyne Lidars



- Scanners have a number (16, 32 or 64) of laser beam / detector pairs.
- The 2D slice is swept through the environment.
- Update rates of 10Hz, hundreds of thousands of points per minute.

Other 3D Laser Configurations

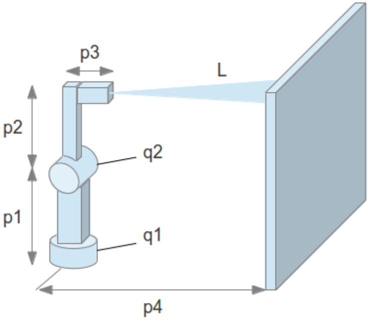
- Other commercial systems from a number of manufactureres (e.g. Riegl)
- Principles are similar to Velodyne.

Outline

1. 3D Laser Scanners
2. 3D Laser Scanner Calibration
3. Time of Flight Cameras
4. Structured Light Cameras

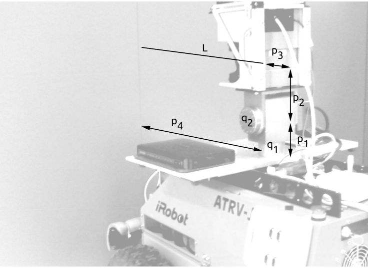
2D Laser + Actuator

- In order to obtain a good estimate of H and a consistent 3D scan, we need to know precisely:
  - The mounting position and orientation of the laser mirror center.
  - The link lengths of the actuator system.
  - The precise actuator joint values.
- Calibration routines are designed to estimate the link lengths and time delay.



2D Laser + Actuator

- In order to obtain a good estimate of H and a consistent 3D scan, we need to know precisely:
  - The mounting position and orientation of the laser mirror center.
  - The link lengths of the actuator system.
  - The precise actuator joint values.
- Calibration routines are designed to estimate the link lengths and time delay.



Velodyne Calibration

- Commercial 3D lasers come with a factory calibration.
- In rare cases additional re-calibration may be performed.
- The important parameters to estimate are the positions and orientations of each of the laser beam detectors, relative to the center of rotation.
- Difficult problem, calibration patterns are not straight-forward to obtain.

Velodyne Calibration

- Commercial 3D lasers come with a factory calibration.
- In rare cases additional re-calibration may be performed.
- The important parameters to estimate are the positions and orientations of each of the laser beam detectors, relative to the center of rotation.
- Difficult problem, calibration patterns are not straight-forward to obtain.

Velodyne Calibration

- Commercial 3D lasers come with a factory calibration.
- In rare cases additional re-calibration may be performed.
- The important parameters to estimate are the positions and orientations of each of the laser beam detectors, relative to the center of rotation.
- Difficult problem, calibration patterns are not straight-forward to obtain.

Velodyne Calibration

- Commercial 3D lasers come with a factory calibration.
- In rare cases additional re-calibration may be performed.
- The important parameters to estimate are the positions and orientations of each of the laser beam detectors, relative to the center of rotation.
- Difficult problem, calibration patterns are not straight-forward to obtain.

Extrinsic Calibration

- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

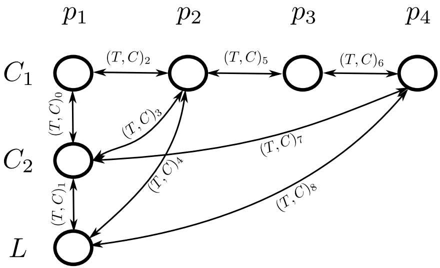
- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

- Extrinsic calibration in the context of 3D lasers refers to refining the estimate of the mounting pose of the laser, relative to a set of other sensors.
- Other sensors of interest could be:
  - Vehicle odometry / center of vehicle coordinate system.
  - A kinematic model of a robot manipulator (hand-eye calibration).
  - Other range sensors.
  - Cameras.

Extrinsic Calibration

- Problem usually posed as an optimization problem over a graph of sensor poses.
- Frequent use of calibration patterns, detectable by all sensors.
- Several heterogeneous sensors with different reference frames.



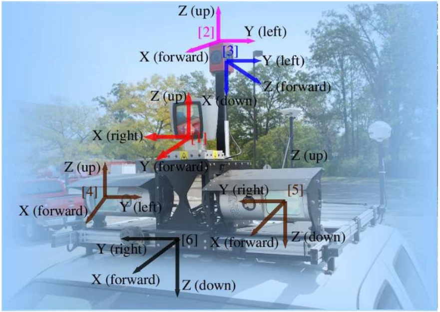
Extrinsic Calibration

- Problem usually posed as an optimization problem over a graph of sensor poses.
- Frequent use of calibration patterns, detectable by all sensors.
- Several heterogeneous sensors with different reference frames.

Image from [1]

Extrinsic Calibration

- Problem usually posed as an optimization problem over a graph of sensor poses.
- Frequent use of calibration patterns, detectable by all sensors.
- Several heterogeneous sensors with different reference frames.



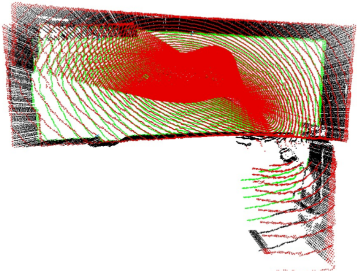
[1] Velodyne, [2] Ladybug3 (actual location: center of camera system), [3] Ladybug3 Camera 5, [4] Right Riegl, [5] Left Riegl, [6] Body Frame (actual location: center of rear axle)

Image from [1]

Extrinsic Calibration

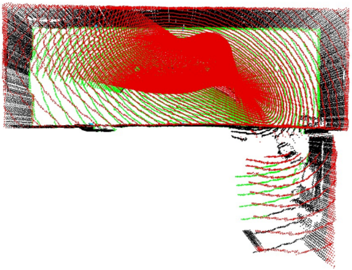
Stop-scan-go vs. scanning while moving

- 3D laser scans suffer distortions when the sensor is moving with a significant speed (wrt scanning time).
- For a 2D laser / actuator pair distortion effects occur at low speeds (1m/s).
- For Velodyne type sensors effects are only significant when moving at speeds of > 10km/h.
- A typical pattern for older research platforms is to take 3D scans when stationary.



Stop-scan-go vs. scanning while moving

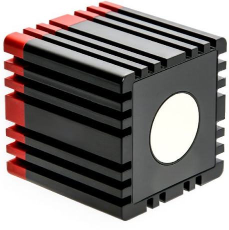
- 3D laser scans suffer distortions when the sensor is moving with a significant speed (wrt scanning time).
- For a 2D laser / actuator pair distortion effects occur at low speeds (1m/s).
- For Velodyne type sensors effects are only significant when moving at speeds of > 10km/h.
- A typical pattern for older research platforms is to take 3D scans when stationary.



Outline

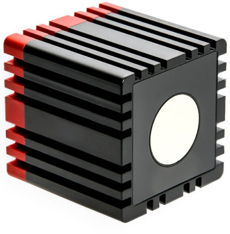
1. 3D Laser Scanners
2. 3D Laser Scanner Calibration
3. Time of Flight Cameras
4. Structured Light Cameras

Time of Flight (ToF) Basics



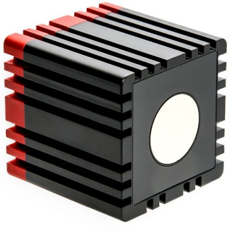
- Time of Flight cameras use the same principle as time of flight lasers.
- Instead of a single beam, a light wavefront is sent.
- The reflected signal is measured with a CMOS sensor.

Time of Flight (ToF) Basics



- Time of Flight cameras use the same principle as time of flight lasers.
- Instead of a single beam, a light wavefront is sent.
- The reflected signal is measured with a CMOS sensor.

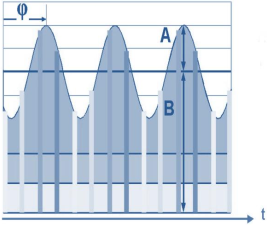
Time of Flight (ToF) Basics



- Time of Flight cameras use the same principle as time of flight lasers.
- Instead of a single beam, a light wavefront is sent.
- The reflected signal is measured with a CMOS sensor.

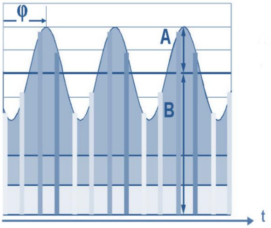
Light Modulation

- The detection range of the camera depends on the modulation frequency for the emitted light.
- The default modulation frequency for the sr4000 is 30MHz.
- This results in an ambiguity range of 5 meters.
- Filters based on reflected intensity are employed to avoid fold back effects.



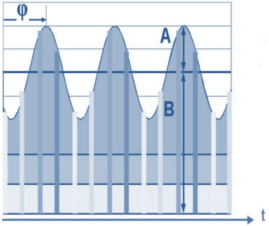
Light Modulation

- The detection range of the camera depends on the modulation frequency for the emitted light.
- The default modulation frequency for the sr4000 is 30MHz.
- This results in an ambiguity range of 5 meters.
- Filters based on reflected intensity are employed to avoid fold back effects.



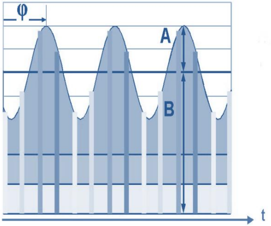
Light Modulation

- The detection range of the camera depends on the modulation frequency for the emitted light.
- The default modulation frequency for the sr4000 is 30MHz.
- This results in an ambiguity range of 5 meters.
- Filters based on reflected intensity are employed to avoid fold back effects.



Light Modulation

- The detection range of the camera depends on the modulation frequency for the emitted light.
- The default modulation frequency for the sr4000 is 30MHz.
- This results in an ambiguity range of 5 meters.
- Filters based on reflected intensity are employed to avoid fold back effects.



Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

Limitations

- Time of Flight cameras suffer from similar limitations as other time of flight sensors.
- Common issues include:
  - Ambiguity of measurements.
  - Multiple reflections.
  - Mixed measurements.
  - Sensitivity to material reflectance.
- In addition, TOF cameras are very sensitive to background lightning and do not operate well outdoors (in strong sunlight).

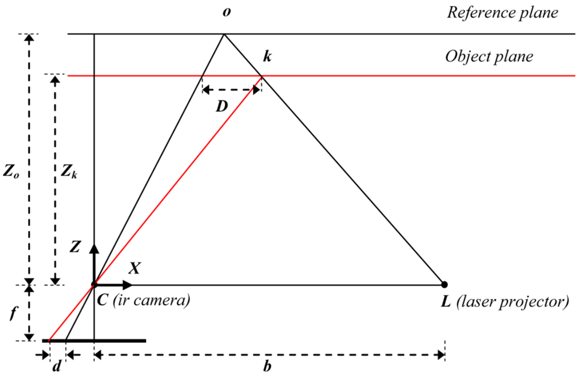
Outline

Structured Light Basics

- A structured light camera works by projecting a known light pattern to the scene.
- Knowledge of the projected pattern is then used for triangulation.

Structured Light Basics

- An image of the projected pattern is taken at a known distance, stored and used as a virtual camera.

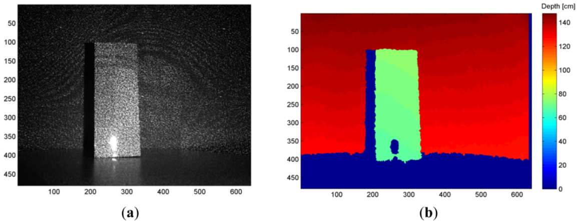


1

[1] Figure from [2]

Projected Patterns

- The Kinect uses a (pseudo-)randomly distributed speckled pattern.
- Each speckle looks differently flat at different distances, due to a special lens.
- The Kinect/PrimeSense camera uses IR light, but visible light is also possible.



2

[2]Figure from [2]

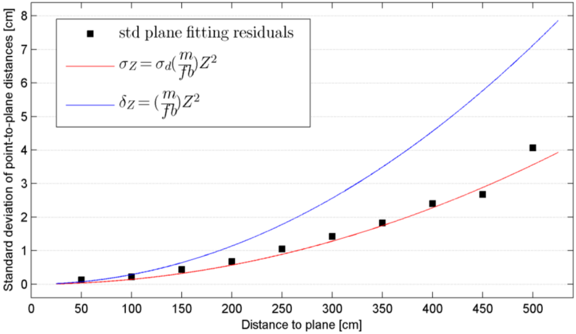
Projected Patterns

- The Kinect uses a (pseudo-)randomly distributed speckled pattern.
- Each speckle looks differently flat at different distances, due to a special lens.
- The Kinect/PrimeSense camera uses IR light, but visible light is also possible.

Error Models

- Errors for structured light cameras grow with the square of the distance to objects.
- Strong quantization effects

2



3

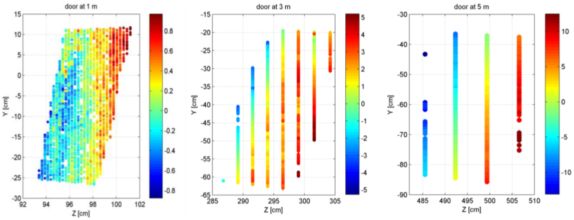
[2] Results from [2]

[3] Figure from [2]

Error Models

- Errors for structured light cameras grow with the square of the distance to objects.
- Strong quantization effects

2



(a) (b) (c)

3

[2]Results from [2]

[3]Figure from [2]

Limitations

- Suffer from illumination variance.
- "Pollute" the scene.
- Quantization and square distance error can be prohibitive.
- ... but also many advantages.

References

Gaurav Pandey, James R. McBride, and Ryan M. Eustice.
Ford campus vision and lidar data set.
International Journal of Robotics Research, 30(13):1543–1552, 2011.

Kourosh Khoshelham and Sander Oude Elberink.
Accuracy and resolution of kinect depth data for indoor mapping applications.
Sensors, 12(2):1437–1454, 2012.

Sensors and Sensing
3D Range Sensing

Todor Stoyanov

Centre for Applied Autonomous Sensor Systems
Örebro University
Sweden