Localized Imaging and Mapping for Underwater Fuel Storage Basins

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Spent Nuclear Fuel (SNF) Storage

Current SNF storage sites

SNF is stored in water pool to shield its radioactive properties

Source: United States Department of Energy
Human Inspection is infeasible

Source: TWI Ltd.
Current SNF Inspection Methods

Source: Unit 4 Spent Fuel Pool Inspection 2012, Fukushima Daiichi
Existing Inspection Examples

Storage Conditions of Reactive Metal Fuel in L-Basin at the Savannah River Site

Defense Nuclear Facilities Safety Board
Technical Report

January 2013

Source: Defence Nuclear Facilities Safety Board

Savannah Rivers Site’s ageing cracked SNF containers
Remotely Operated Sensor Package

A robot-mounted sensor pod will provide localised inspection, enabling operators to pinpoint sensor reading locations relative to 3D structure.
Remotely Operated Inspection System

Localised Data Collection

Model Reconstruction
Underwater Mapping

- Underwater & real-time data collection
- 3D reconstruction using image sequences (Structure from Motion)
Today’s Talk...

Localised Data Collection

Model Reconstruction
Inspection Sensor Pod

- Inertial Measurement Unit (IMU) (250Hz)
- GigE Machine Vision Cameras (10Hz)
- Lumen subsea light
- Bar30 pressure sensor
Time-Synchronisation of Sensors

- Each sensor uses its own clock to time stamp data
- Essential to ensure accurate sensor fusion for localisation
- Sensors record at various rates
- Clock drifts!

![Diagram showing IMU (250Hz), Left Camera (10Hz), Right Camera (10Hz) over Time]
Hardware Synchronisation

Right Cam

Left Cam

IMU (Front)

(Master Clock)

Left Camera

Right Camera

Clock Signal

IMU
Waterproof enclosure

- Tether Wires
- Waterproof Enclosure (polycarbonate)
- Enclosure End Cap (aluminium)
Odometry Algorithms

- Inertial Odometry is commonly used but it drifts.
- Visual Odometry are effective but for small motions (DSO, ORB-SLAM).

J Engel et al.
“DSO”

R Mur-Artal et al.
“ORB-SLAM”
Visual-Inertial Odometry (VIO) Algorithm

› Combines the bests from visual and inertial information
› Utilizes synchronised sensor information
Stereo Triangulation for VIO

The corresponding points are triangulated into the 3D world
Camera moves...

IMU Integration
A sequence of camera movements
Details of the VIO system

- A VIO system consists of a frontend and a backend parts
- Data association Frontend
  Optimisation Backend

- IMU Measurements
- Stereo Camera Frames
- Frontend (Data Association)
- Visual Features
- Backend (Optimisation)
- State Estimate
Data Association Frontend

- Shi-Tomashi Corner Detector
- Lukas-Kanade Optical Flow feature tracking algorithm (up to 200Hz)
Data Association Frontend

Left Camera Frame

Right Camera Frame
A sequence of camera movements

IMU Integration

Camera Trajectory
Optimisation Backend

Camera Trajectory

Visual Features

Camera Trajectory

Source: F. Dellaert and M. Kaess, "Factor graphs for robot perception"
Optimisation Using Graphs

Graph

X1 X2 \ldots Xn
Graph Optimisation

- Specifies the relationships between variables and measurements

$X = \text{Camera States}$

(Position, Orientation, ...)

Visual Measurement

IMU Measurement

Time
Graph Optimisation

Solution is given by the optimal estimate that best explains all sensor measurements

Also known as **Maximum a Posterior Estimate (MAP)**
VIO Datasets Trials

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<tr>
<th>Absolute Trajectory Error (ATE)</th>
<th>RMSE</th>
<th>Mean</th>
<th>Median</th>
<th>Std</th>
<th>Min</th>
<th>Max</th>
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<td>Positional (m)</td>
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<td>0.123</td>
<td>0.118</td>
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<td>0.025</td>
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<td>Translational (m)</td>
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<td>0.032</td>
<td>0.027</td>
<td>0.020</td>
<td>0.001</td>
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<td>Rotational (°)</td>
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<td>0.407</td>
<td>0.411</td>
<td>0.016</td>
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<th>Relative Pose Error (RPE)</th>
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<td>EuRoC VH_01 Dataset</td>
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Proposed

Groundtruth
Summary

- A localised inspection solution is essential to ensure an efficient, consistent, and accurate inspection process.
- A visual-inertial odometry algorithm is presented to allow accurate localisation in an underwater environment.
- A time-synchronised sensor pod is required for the data to be sent instantaneously and concurrently.
- With localisation information and synchronised data, 3D models can be reconstructed.
Thank you!

› Andrew Tallaksen
› Lawrence Papincak
› Sudharshan Suresh
› Heather Jones
› William Whittaker
› Michael Kaess