Overview

- Background and Component Description
- Reference Requirements
- Visual Odometry Technical Description
- Test Site
- Platform
- Ground Truth
- Visual Odometry Results
- Conclusions
- Questions
Background

**TASK: Localisation**
- Local Map
- Global Map
- Sensor Fusion
- Trajectory tracker
- Localisation

**ACTION: Platform Specific Localisation Sensors**
- Sensor Interface
- Sensor Configuration
- Sensor History
- Sensor Feedback Safety Monitor
- IMU/Tilt
- Wheel Odometry
- Compass
- GPS/Radio beacon
- Sun/Star tracker
- Visual Odometry

**Internal Sensors**
- Sun/Star tracker
- GPS/Radio beacon
- Visual Odometry

**External Sensors**
- IMU/Tilt
- Wheel Odometry
- Compass
Reference Requirements

- Shall provide a 6DOF relative pose estimate at a rate of 1Hz. *Pose includes translation and rotation information using the x axis as straight ahead, y axis as to the right and z as downwards.*

- Shall provide a pose with an accuracy equal or better than 1% of the distance travelled
  - Maximum rover speed of 10cm/s
  - Maximum rover rotation of 10deg/s

- Shall provide a pose with an accuracy equal or better than 5% of the distance travelled
  - Maximum rover speed of 200cm/s
  - Maximum rover rotation of 20deg/s

- The Rover shall know its relative location, w.r.t. the last stopping place where topographic information was acquired for path generation, to better than 10 cm at all times during its locomotion.

- Pose accuracy shall be verified in a quarry with Martian analogue and at the ESTEC site. *Traverses shall consist of 10m, 50m, and 100m ranges.*

- Shall provide an indicator to show the confidence of the estimate accuracy level is less than 1%
Reference Requirements – Cont.

- Cameras shall have auto exposure, shutter and gain adjustments without manual input.
- The system shall not be sensitive to projected shadows.
- Shall provide pose estimated in daylight conditions. *During external trials the time duration will be influenced by seasonal and environmental conditions.*
- Shall provide a strategy to continue operations when the sun is in the FOV.
- Shall have the following modes; a health check and self calibration, Odometry acquisition, Video acquisition and image acquisition.
- VOS shall provide a pose estimate in Vision Sensor reference frame. *Note the localisation system will do the conversation between reference frames.*
Visual Odometry - High Level Overview

• Motion estimation from images can be achieved by feature point locations easily identifiable and repeatable across multiple images, for example corners.

• By tracking (~100) very good performance can be achieved.

• This imposes a static world assumption on the system although in reality, some amount of dynamic world motion can be tolerated by the system.
Visual Odometry – Camera Selection

• In the estimation it is assumed that all observations of feature points within a single image happen at exactly the same time.
• Cameras are used with global shutter systems, instead of rolling shutters.
• Choosing to use a stereo camera alleviates the depth perception problem encountered with a mono camera.
• When dealing with a stereo pair, it is important they are both captured at exactly the same time.
• Assumption that the rows across the pair of images are exactly aligned, as this aids feature matching.
Visual Odometry – Image Rectification

- Images from cameras are not perfect;
  - they typically suffer from lens distortion. To fix this, both images are rectified.
  - Chromatic aberration. Dependant on wavelength (not an issue here)
- An example of image rectification carried out during the Tubney Quarry trials: the left image is un-rectified, the right image has been rectified.
Visual Odometry – Feature Extraction

- Feature points are identified within the image. In our system, we use the FAST corner extractor. FAST produces a large number of candidate corners at a small computational cost.
- Obviously, some of these corners will be better than others, so they are ranked based on a “good corner” score (here we use the Harris score).
- To achieve robustness to motion blur, we run FAST at different scales of the original image, known as “pyramid levels”.
- If we just took the top $N$ features, we typically find them clustered around a few strong corners in the image. Instead, we force the features to spread out across the image using a quad tree. This constrains the number of features in any particular point in the image, as well as the maximum number of features tracked.
Visual Odometry – Feature Matching

- When features are initialized for the first time, they need to be found in both the left and right image of the stereo pair.
- A feature on row $k$ in the left image, can be assumed to line up row $k$ in the right image.
- 1D search using mean SAD (sum of absolute differences) to compute the best matching score.
Visual Odometry – Temporal Matching

- Temporal matching is the process of matching two frames from time $t$ to $t+1$.
- The camera could have undergone arbitrary motion between the two capture times.
- A method called Binary Robust Independent Elementary Features (BRIEF) is used to match the features.
- BRIEF provides a integer pixel location within the image, however better performance is achieved if we refine this estimate if with sub-pixel matching. This refinement is performed using Efficient Second Order Minimization (ESM).
Visual Odometry – Motion Estimate

- Once a set of refined feature matches between two stereo frames have been generated, the 6-DoF motion between the two frames can be computed starting with an initial RANSAC (RANdom SAmple Consensus) step that highlights and removes any outliers.
- A Least squares minimization is then performed using an $m$-estimator for robustness. After this step, any new outliers are also removed.
- Once the motion estimation has been completed and outliers removed, new features are added in the appropriate locations.
Test Site

- UK site
- 300x200m
- Sandy
- Little vegetation
Platform - INDIE

- 6 wheel drive, 2 wheel steer
- On-board processing with Autonomous
  » Localisation
  » Navigation
  » Planning
  » Sensor acquisition
- Passive suspension
- 3.5 hour operation time
- Good terrain traversability
- Stereo cameras on PTU
- IMU
- GPS data tagging
Ground Truth

- DGPS NovAtel sub-centimetre @ 1Hz
Visual Odometry Tests

• Generate a variety of tests that address the requirements
  » Traverse in a straight line over 100m distance
  » Traverse with 360 degree rotation along the path
  » Traverse into Direct sunlight
  » Traverse across a Slope to produce side slip
  » Traverse containing all previous components
  » Traverse in a “Snake” motion
  » Traverse two large loops
  » Approach a gully face
  » Astronaut follow
  » Shadows changing in the field of view

• Indoor environment
  » Astronaut follow
  » 90 traverse and return to the start
Visual Odometry Results - 100m traverse

[Graph showing visual odometry results for different distances.]
VOR - Small traverse with 360 degree rotation
VOR - Traverse into direct sunlight
VOR – 256m Traverse

[Diagram showing traverse data with DGPS and VO tracks]
VOR – Snake Traverse

[Graph showing DGPS and VO trajectories over a traverse]

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VOR – Approach Numerous times
VOR – Astronaut Follow
VOR - Shadows
VOR - TASI

TAS-I
VOR – TASI 90m

![Graph showing VOR-TASI 90m data]

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SCISYS
## Visual Odometry - Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Total Distance (m)</th>
<th>RMS error (m)</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>100m straight line traverse</td>
<td>106.39</td>
<td>0.33</td>
<td>0.31</td>
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<tr>
<td>Traverse with rotation</td>
<td>37.36</td>
<td>0.017</td>
<td>0.1</td>
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<td>Direct sunlight</td>
<td>16.57</td>
<td>0.06</td>
<td>0.4</td>
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<td>Slope</td>
<td>7.68</td>
<td>0.01</td>
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<td>Around the quarry</td>
<td>256.13</td>
<td>0.99</td>
<td>0.38</td>
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<td>Snake</td>
<td>64.85</td>
<td>0.72</td>
<td>1.1</td>
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<tr>
<td>High Speed</td>
<td>50</td>
<td>1.65</td>
<td>3.3</td>
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<tr>
<td>Loops</td>
<td>94.96</td>
<td>0.18</td>
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<td>Gully</td>
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<td>Approach</td>
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<td>0.3</td>
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<tr>
<td>Astronaut follow</td>
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<td>Long left</td>
<td>51.48</td>
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<tr>
<td>Shadows</td>
<td>0</td>
<td>0.44</td>
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<tr>
<td>Return to tent</td>
<td>5.3</td>
<td>0.26</td>
<td>0.47</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1843.26 (total)</strong></td>
<td><strong>44.94 (total)</strong></td>
<td><strong>0.6 (average)</strong></td>
</tr>
</tbody>
</table>
Further Work - Chile
Further Work - GFreeNav
Further Work – Representative Hardware

- Evaluation the suitability of the OVO and localisation architecture on space qualified hardware (ExoMars breadboard (75MIPS Leon2) as a baseline).
- Testing on flight-representative hardware using image data captured during a trials in the Atacama Desert showed covering a distance of 0.85km.
- Results showed mean time to process image frames below the required 10s per image frame.
- Positional estimates providing less than ~1.5% RMS error.
Conclusions

- This work sought to evaluate a state of the art visual odometry breadboard for EGP localisation.
- The extensive in results demonstrate that the component satisfies the XROB requirements for mobile platform missions with a high level of performance.
- Tested in a variety of environments,
  - local quarry trials carried out in the UK
  - Clean room at TAS-I
  - A complementary version of the component was tested in the Atacama Desert.
- Provides a high degree of confidence in the proposed technology as this environment offered the complete range of vision/terrain conditions expected on a Moon/Mars flight mission
- Given the results of this activity where the component was integrated as part of a complete GNC solution it indicates that the technology is at TRL 5 – “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”. 
VOR - Chile

| Chile | 1050 | 17.35 | 1.6 |

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