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Reconstructing JET using LIDAR-Vision fusion

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Abstract

We present work describing the 3D mapping of the inside of the Joint European Torus using a combined LIDAR-Vision measurement and navigation system from the Oxford Robotics Institute. We compare the point cloud model with the CAD models of the JET installation using numerical methods. Initial results show sub-mm accuracy over part of the vessel when conditions are right. conclusions about the applicability of LIDAR systems to mapping and localisation problems within a Fusion environment. We also briefly review the potential of radiation hardening LIDAR scanners for wider use in Fusion contexts.

Keywords: Sensor Fusion, LIDAR, Vision, Remote Handling, Scanning

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1. Introduction

The Joint European Torus (JET) is currently the world's largest operational nuclear fusion research reactor, located at the Culham Science Centre in Oxfordshire, UK. The containment vessel of the JET machine is a huge, complicated assembly with a myriad of components, the location and alignment of which are crucial for fusion plasma operation. During operation, the extreme heat and high magnetic flux inside the machine puts a large mechanical and thermal load on components. This results in a need for regular inspection and maintenance of these in-vessel components.

During each maintenance shutdown a multitude of components are removed and re-installed by the Remote Maintenance/Remote Handling (RM/RH) systems. The RM operations are carried out by the JET RH Operations Team, part of RACE (Remote Applications in Challenging Environments).

For the purposes of inspection, measurement and component location verification, a high-resolution stereogrammetry survey is carried out of the entire interior of the JET Vacuum Vessel at the start and end of each maintenance campaign. This is done by means of dual-camera Stereo Photogrammetry surveys, High-Resolution single camera surveys and precise tile gap measurements using the laser "Gap Gun". During the 2016/17 Shutdown, the JET RH team spent 119hrs on "manual" (person-in-the-loop) inspection tasks, requiring a full 5-person RM shift team for most of this time.

Future RM applications, in fusion facilities such as ITER and EU-DEMO (DEMOnstration Fusion Reactor), will require fully remote inspection and maintenance capabilities, which should be automated to the greatest extent possible in order to increase efficiency and reduce costs. This creates a need for alternative measurement, localisation and navigation equipment. The reactors will also produce large amounts of gamma radiation, even when shut down for maintenance, placing severe contraints on the sensor electronics, which will need to cope with a nimimum of 1 kGy/hr dose rates and a TID (Total Integrated Dose) over its operational lifetime of around 10 MGy [1]. In contrast, the levels of gamma-radiation inside the JET vessel are still low enough to allow consumer-grade electronics to survive unprotected, and hence the latest advancements in LIDAR-Vision fusion systems in the field of Autonomous Vehicles can be leveraged.

What follows is a description of the work carried out during the 2016/17 JET Maintenance Shutdown, using an array of COTS sensors to gener-

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ate a metrology dataset of the inside of the JET torus including stereo and monocular visual and LIDAR point cloud data. This was used to assess the benefits, limitations and feasibility of using these technologies for current and future RH applications such as mapping/inspection of components and localisation of RH equipment.

2. Suitability of LIDAR-Vision fusion in nuclear fusion environments

LIDAR is currently being used in the designs for the ITER IVVS (In-Vessel Viewing System), to be used for static in-vessel inspection of the ITER vessel. In this system, the laser beam used for measurement is led into the vessel using radiation tolerant optical fibres, enabling the laser drive circuits to be kept away from the most active areas [2]. Using test versions of this system, sub-mm measurement accuracy has been achieved [3], and the system is designed to be able to cope with a gamma radiation dose of 5kGy/h with a TID of 10MGy.

Progress has also been made in the design of components necessary for constructing more portable radiation tolerant LIDAR systems. Components such as Laser drivers [4], transimpedance amplifiers [5], receiver frontend components [6] and time-to-digital converters [7, 8] have been developed and/or tested by various groups to a TID tolerance of several MGy. Optical systems such as lenses remain challenging, but alternatives exist [2].

When it comes to visual cameras, progress has been made in designing and testing digital CMOS cameras for the ITER RM systems to a level of 1 MGy TID [9], providing some confidence that a 10 MGy CMOS camera will be feasible some years in the future.

3. Data collection

The data collection was carried out in May 2017 with the, help of the JET RH Operations Team during the 2016/17 JET Maintenance Shutdown.

3.1. Data collection device

The "NABU" sensor is a small, self-contained, portable surveying solution produced by the Oxford Robotics Institute (ORI), utilizing standard COTS hardware in a custom 3D printed housing. It contains a Bumblebee X2 stereo camera, twin Hokoyu 2D-LIDAR scanners in a push broom configuration and two HD colour fisheye monocular cameras. It is entirely self contained with computer and data collection hardware alongside an on-board battery that provides several hours of operation without any external power supply needed. Coloured point cloud surveys are generated using the stereo camera for odometry estimation.

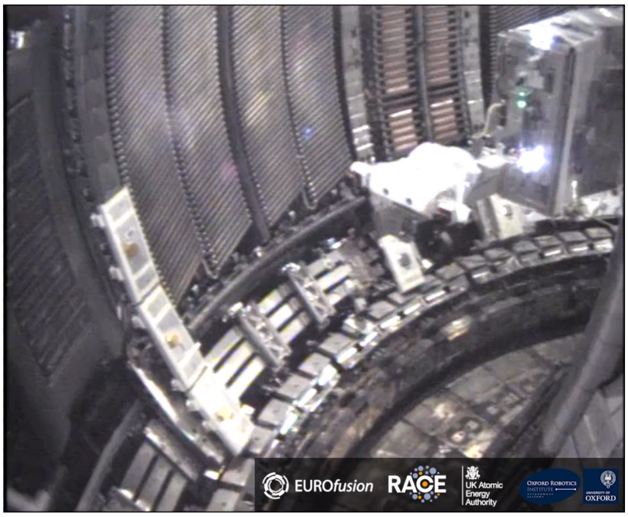

Figure 1: NABU performing in-vessel data collection. Image captured by JET in-vessel maintenance cameras.

To allow the NABU to be recovered from having been inside the controlled environment of the vacuum vessel, the external fans were removed and covered over. The device was encased in a protective plastic cover to protect against contaminated dust ingress, leaving only the camera lenses and LIDARs exposed.

3.2. Transportation of sensor

The NABU was transported into the vessel using the "Tile Carrier Transfer Facility" Boom, also known as the "Octant 1 Boom", an 8 meter long articulated transporter used to carry tools and materials into and out of the vessel as pert of the JET RH system.

The Boom was fitted with an end-effector called the "Roll End-Effector", which provides the Boom with a rotational joint allowing the payload to be oriented vertically or horizontally as required. Using custom-made bracketry including two repurposed tile carriers, the NABU was fitted to the Boom and carried into the JET vessel (Figure 1).

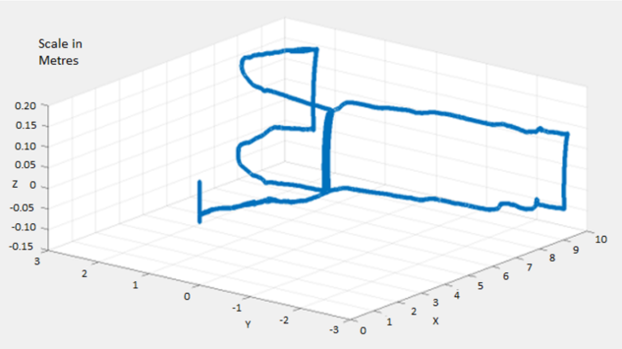

Figure 2: 3D-path generated from Stereo Camera Visual Odometry. Note scale on Z-axis.

3.3. Data collection

Using the Octant 1 Boom, the NABU was moved along the centre of the vessel, capturing as much of the Torus as possible given the limitation that the Octant 1 Boom only reaches about 66% of the torus-shaped vessel. At the same time, joint position data was collected from the Boom control system.

4. Processing data

The data collected included high-resolution stereo and mono video files, a timestamped 3D-path calculated using Visual Odometry (VO), and a large number of timestamped 2D LIDAR slices. The VO was calculated using techniques similar to that used in [10]. The 3D-path produced can be seen in Figure 2.

Algorithms and software developed by ORI was used to stitch together the 2D-scan slices into a 3D-pointcloud of the inside of the JET vessel. The points were assigned a colour using the data from the monocular cameras, resulting in a coloured 3D-pointcloud [11].

The CAD model (hereafter referred to as the ”mesh”) used for the comparison was generated from the Configuration Model kept during the Shutdown by the JET RH Operations Team and exported as an .STL file.

It was decided to focus on an area around the Octant 3 port since the distinctive LHCD antenna postioned in the port simplified CAD alignmen t. Using the GPL licenced software CloudCompare [12], the point cloud produced was aligned with the CAD model. Initial alignment was carried out manually, and then the standard ICP (Iterative Closest Point) algorithm was used for fine alignment.

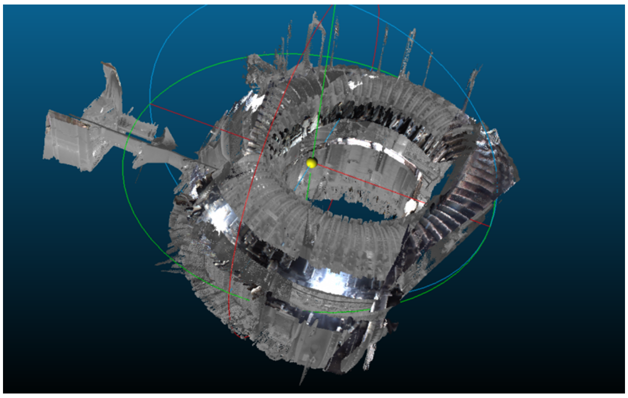

Figure 3: Full 3D-model based on data collected by LIDAR 1. The left-hand part of the scan is the Tile-Carrier Transfer Facility which houses the Octant 1 Boom.

The standard CloudCompare mesh-to-cloud distance measurement function was used to determine the distance between the .STL triangle surfaces and the NABU-generated 3D-model. The algorithm works by defining the distance to the nearest triangle as either the orthogonal distance from the point to the triangle plane, if the orthogonal projection of the point on this plane falls inside the triangle. If this is not the case, the distance to the nearest edge is taken.

5. Results

The data collection including setup and teardown added 4 hours of extra measurement time to the Shutdown total of 119h.

The 3D-models produced with LIDAR 1 alone were aligned as intended. However, a calibration issue with LIDAR 2 meant that the data from both LIDARs could not be used to make a unified model. Because of this, the models presented here uses data from LIDAR 1 only.

Examples of the 3D pointclouds produced using LIDAR 1 in isolation can be seen in Figures 3, and 4.

The output of the mesh-to-cloud (CAD-to-Pointcloud) distance measurement of the Octant 3 section of the torus can be seen in Figure 5 as a heatmap, showing the signed distances from each point to the closest part of the mesh.

The histogram in Figure 6 graphs the output from , 99% of the distances are in the -0.06 to +0.1

Figure 4: 3D-pointcloud of JET outer wall. Compare to left-hand side of Figure 1

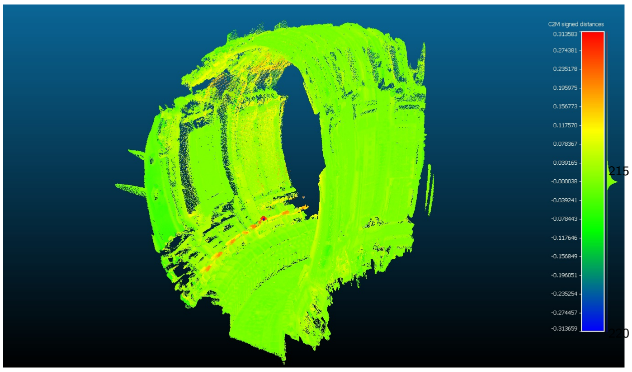

Figure 5: Heatmap of cloud-to-mesh distances calculated in area by the Octant 3 port.

m (-60 to +100 mm) range, and the dominant class with 807270 points covers the range of -0.002488209 to +0.0000380427 m (-2.5 to +0.003 mm) error.

6. Discussion

The results of the data collection, processing and evaluation as discussed in the previous sections have succeeded remarkably well, providing data with sub-mm accuracy for most of the scanned areas. The COTS LIDAR devices have coped well with the reflective surfaces inside the vessel as well as the challenging geometries.

The small hump on the left side of the histogram in Figure 6 is due to “double-walling” in the data, caused by the NABU moving past the same location twice but (according to the VO) not following the exact same path. The thick tail seen on the right side of the histogram is likely to be related to the same phenomenon. This drift due to the limitations of the VO can be corrected by generating a more accurate 3D-path using angular sensor data from the Boom. Combining this with the original 3D-path using Kalman filtering should improve the pointcloud accuracy significantly. This will be done in follow-up publications.

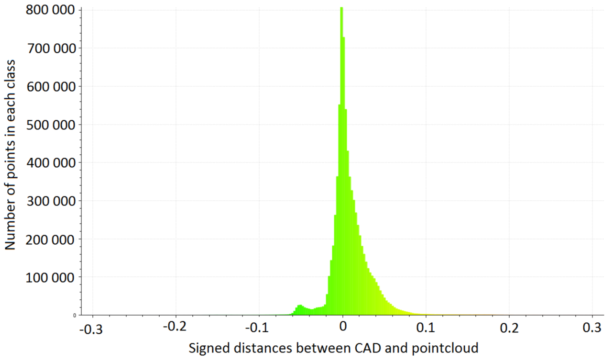

Figure 6: Histogram of C2M signed distances. 7712744 values, 256 classes. Mean distance = 0.008243, Standard deviation = 0.022152

The quality of the results measuring the ITER-Like wall in JET matches the results in [2, 3] and demonstrates the data collection capability of portable LIDAR scanners in future Fusion in-vessel environments, and provide a clear motivation for the development of radiation-tolerant LIDAR scanners for use in these more extreme environments. From the perspective of JET, this allows for rapid measurement of the vessel with reasonable accuracy. Complementing the current data collection with regular 3D-scanning of the vessel would be highly beneficial, and could enable the use of automated component detection and/or measurement systems to be developed and tested.

A further use is in precisely positioning 14MeV neutron sources inside the JET/ITER/DEMO vessel for neutron detector calibration. Indeed, the calibrations which took place during the 2016/17 JET Maintenance shutdown were limited by the fact that the positioning uncertainty of the source when held by the RH equipment was +-1 to 2cm [13]. If this could be improved then the accuracy of future neutron calibrations could be improved significantly.

Finally, the EU-DEMO fusion proof-of-concept reactor will require large numbers of robotic remote maintenance systems operating as autonomously as possible. If 3D-LIDAR data using mobile self-contained scanners can be collected successfully in a fusion context, this will vastly increase the capability of Fusion RM systems given the development of radiation-tolerant LIDAR scanners.

7. Conclusions

The experiments detailed in this paper has confirmed the suitability of using portable LIDAR scanners in a nuclear fusion context given the requsite improvements in radiation tolerance. It has been shown that the data quality of standard COTS 2D-LIDAR scanners is high enough to provide sub-mm accuracy 3D-models in the right circumstances. These circumstances are now also better understood. The results have been discussed and potential future applications of this technology suggested. Future work includes further processing of the data already collected, merging in data from LIDAR 2 after correcting for the calibration offset, as well as looking into automated localisation and model interpretation techniques to further explore ways of using the data for remote maintenance tasks.

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