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Reconstructing JET using LIDAR-Vision fusion

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ABSTRACT

Commercialising Nuclear Fusion requires considerable advances in sensors for accurately localising Remote Maintenance systems. One promising technology is LIDAR, frequently used for robotic positioning and navigation. We present work describing the 3D mapping of the inside of the Joint European Torus using a combined LIDAR-Vision fusion based measurement and navigation system from the Oxford Robotics Institute. We generate a point cloud model from our measurements and compare it with CAD models of the JET vessel using numerical methods. We show that millimeter and sub-millimeter accuracy of results are possible under the right circumstances, with nearly 10% of points having a measurement error of between 2.5 and 0.03 mm compared to the CAD model. We briefly review the potential of radiation hardening LIDAR scanners for wider use in Fusion contexts. Finally we draw conclusions about the applicability of LIDAR systems to mapping and localisation problems within fusion environments, and detail further work required.

1. Introduction

The Joint European Torus (JET) is currently the world's largest operational nuclear fusion research reactor. It is operated and maintained by the UK Atomic Energy Authority (UKAEA) on behalf of the EUROfusion consortium and located at the Culham Science Centre in Oxfordshire, UK. The containment vessel of the JET machine is a large, 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 rate of change in magnetic flux inside the machine puts large mechanical and thermal loads on the in-vessel components. This results in a need for regular inspection and maintenance of these 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), the UKAEA's remote maintenance division.

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" [1]. During the 2016/17 Shutdown, the JET RH team spent 119 h carrying out 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 minimum of 1 kGy/hr dose rates and a TID (Total Integrated Dose) over its operational lifetime of around 10 MGy [2]. 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 generate 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.

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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 [3]. Using test versions of this system, sub-mm measurement accuracy has been achieved [4], and the system is designed to be able to cope with a gamma radiation dose of 5 kGy/h with a TID of 10 MGy.

Progress has also been made in the design of components necessary for constructing more portable radiation tolerant LIDAR systems. Components such as Laser drivers [5], transimpedance amplifiers [6], receiver frontend components [7] and time-to-digital converters [8,9] 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 do exist [3].

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 [10], providing some confidence that a multi-MGy CMOS camera will be feasible some years in the future [11].

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 [12] 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.

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 m long articulated transporter used to carry tools and materials into and out of the vessel as part 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 (Fig. 1).

3.3. Collecting data

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.

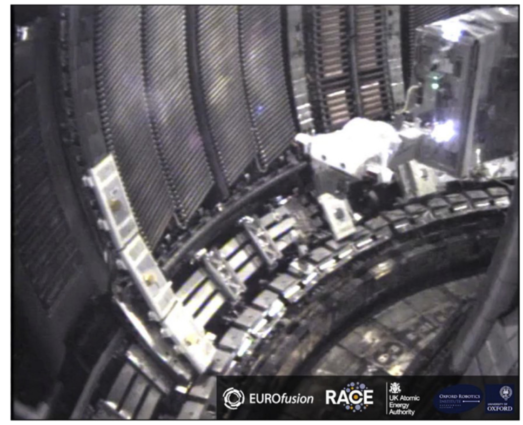

Fig. 1. NABU performing in-vessel data collection. Image captured by JET in-vessel maintenance cameras.

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 [13]. The 3D-path produced can be seen in Fig. 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 [14].

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 positioned in the port simplified CAD alignment. Using the GPL licensed software CloudCompare [15], 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.

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.

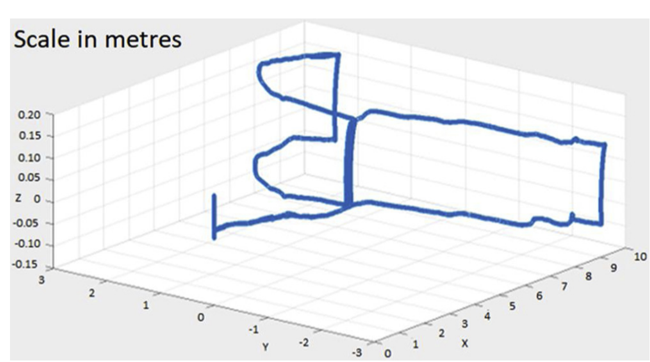

Fig. 2. 3D-path generated from Stereo Camera Visual Odometry. Note scale on Z-axis.

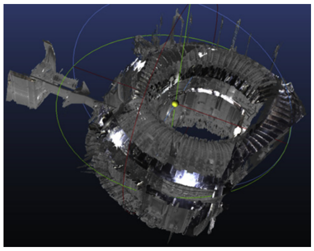

Fig. 3. Full 3D-model based on data collected by LIDAR 1. The left-hand part of the scan is the Tile-Carrier Transfer Facility which houses the Octant 1 Boom.

5. Results

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

Data had been collected with both Hokoyu LIDARs used in the NABU, but a calibration issue with one of them (LIDAR 2) meant that the data from both LIDARs could not be used to make a unified model. However, the 3D-models produced with LIDAR 1 alone were aligned as intended, and as such, 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 Figs. 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 Fig. 5 as a heatmap, showing the signed distances from each point to the closest part of the mesh.

The histogram in Fig. 6 graphs the mesh-to-cloud output, dividing the results up into 256 error distance classes. It shows that 99% of the distances are in the −0.06 to +0.1 m (−60 to +100 mm) range, and the dominant class with 807,270 points covers the range of −0.002488209 to +0.0000380427 m (−2.5 to +0.04 mm) error. The sign of the error signifies direction.

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 and the thick tail on the right side of the histogram in Fig. 6 is due to "double-walling" and other artifacts 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 red marks along the bottom of Fig. 5 is the clearest example of this type of error. This drift 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.

The quality of the results measuring the JET first wall matches the results in [3,4], demonstrates the data collection capability of portable LIDAR scanners in future Fusion in-vessel environments, and leads to a clear motivation for the development of radiation-tolerant LIDAR scanners for use in these more extreme environments. From the

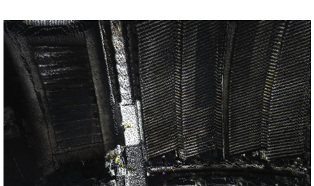

Fig. 4. 3D-pointcloud of JET outer wall. Compare to left-hand side of Fig. 1.

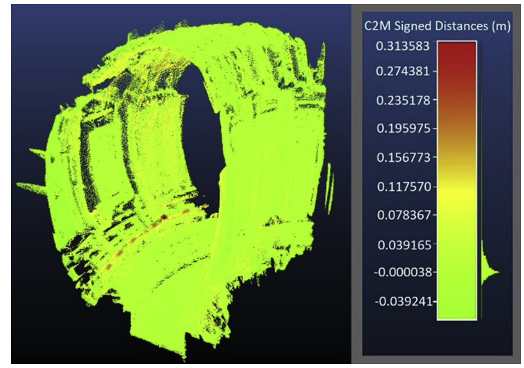

Fig. 5. Heatmap of cloud-to-mesh distances calculated in area by the Octant 3 port. (For interpretation of the references to colour in this figure text, the reader is referred to the web version of this article.)

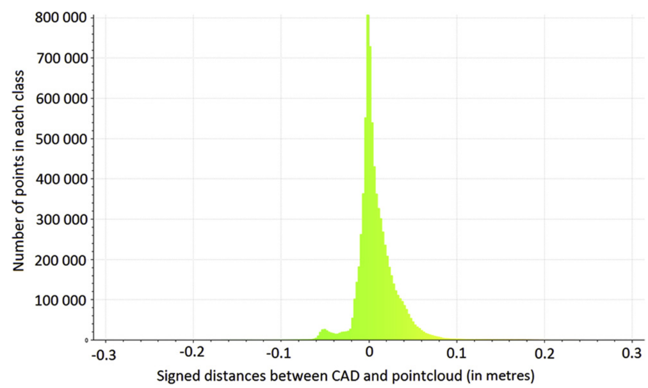

Fig. 6. Histogram of cloud-to-mesh signed distances, with 7,712,744 values sorted into 256 classes. Mean distance = 0.008243, Standard deviation = 0.022152.

perspective of JET, on-board LIDAR 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 14 MeV 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 +−10 to 20 mm [16]. 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 have confirmed the suitability of using portable LIDAR scanners in a nuclear fusion context given the requisite 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 data both LIDARs together 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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References

[1] T. Mindham, et al., Developments in remote metrology at JET, Fusion Eng. Des. 86 (9) (2011) 1855–1858 proceedings of the 26th Symposium of Fusion Technology (SOFT-26).

[2] C. Bachmann, et al., Overview over demo design integration challenges and their impact on component design concepts, Fusion Eng. Des. 136 (Part A) (2018) 87–95.

[3] C. Neri, et al., The upgraded laser in vessel viewing system (IVVS) for ITER, Fusion Eng. Des. 84 (2) (2009) 224–228 proceeding of the 25th Symposium on Fusion Technology.

[4] G. Dubus, A. Puiu, P. Bates, C. Damiani, R. Reichle, J. Palmer, Progress in the design and R&D of the ITER in-vessel viewing and metrology system (IVVS), Fusion Eng. Des. 89 (9) (2014) 2398–2403 proceedings of the 11th International Symposium on Fusion Nuclear Technology-11 (ISFNT-11) Barcelona, Spain, 15-20 September, 2013.

[5] P. Leroux, S. Lens, R. Voorspoels, M.V. Uffelen, W.D. Cock, M. Steyaert, F. Berghmans, Design and assessment of a circuit and layout level radiation hardened CMOS VCSEL driver, IEEE Trans. Nucl. Sci. 54 (4) (2007) 1055–1060.

[6] J. Verbeeck, M. Steyaert, P. Leroux, A & 4 MGy radiation tolerant 8 THzOhm transimpedance amplifier with 50 dB dynamic range, J. Instrum. 8 (02) (2013) 2052.

[7] D. De Jonghe, et al., Design of a radiation tolerant LIDAR receiver with mm accuracy in 0.13 m CMOS, ProRISC 2008: 11th Annual Workshop on Semiconductor Advances for Future Electronics and Sensors, (2008) Stichting voor de Technische Wetenschappen.

[8] Y. Cao, W.D. Cock, M. Steyaert, P. Leroux, Design and assessment of a 6 ps-resolution time-to-digital converter with 5 MGy gamma-dose tolerance for LIDAR application, IEEE Appl. Nucl. Sci. 59 (4) (2012) 1382–1389.

[9] MAGICS Instruments NV, TDC2201 MAGICS Instruments, URL http://www.magics.tech/portfolio/rad-hard-asics/tdc2201/.

[10] V. Goiffon, et al., Radiation hardening of digital color CMOS camera-on-a-chip building blocks for multi-MGy total ionizing dose environments, IEEE Trans. Nucl. Sci. 64 (1) (2017) 45–53.

[11] S. Rizzolo, et al., Multi-MGy total ionizing dose induced MOSFET variability effects on radiation hardened CMOS image sensor performances, 17th European Conference on Radiation and Its Effects on Components and Systems (RADECS) (2017).

[12] Oxford Robotics Institute: Survey Equipment. https://ori.ox.ac.uk/application/survey/.

[13] D. Nister, O. Naroditsky, J. Bergen, Visual odometry, Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2004 Vol. 1 (2004) pp. I–I.

[14] A.D. Stewart, P. Newman, Laps - localisation using appearance of prior structure: 6-dof monocular camera localisation using prior pointclouds, 2012 IEEE International Conference on Robotics and Automation, (2012), pp. 2625–2632.

[15] CloudCompare (version 2.9.1), (2018) http://www.cloudcompare.org/.

[16] P. Batistoni, et al., 14 MeV calibration of JET neutron detectors phase 2: in-vessel calibration, Nucl. Fusion 58 (10) (2018) 106016.