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Developments in Remote Metrology at JET

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.
The need to maximise the operational availability of fusion devices has driven the enhancements in accuracy, flexibility and speed associated with the inspection techniques used at JET. To this end, the remote installation of the ITER-Like Wall (ILW) tiles, conduits and embedded diagnostics has necessitated the adoption of technologies from other industries for their use in conjunction with the JET Remote Handling (RH) system. The novel adaptation of targetless stereophotogrammetry, targeted single-camera photogrammetry and gap measurement techniques for remote applications has prompted a range of challenges and lessons learnt both from the design process and operational experience.

nterfacing Commercial Off-The-Shelf (COTS) components with the existing RH equipment has highlighted several issues of relevance to the developing ITER RH system. This paper reports results from the stereophotogrammetry and the single-camera photogrammetry surveys, allowing analysis of the effectiveness of the RH system as a platform for in-vessel measurement. This includes scrutiny of the accuracy achieved with each technique as well as the impact on the in-vessel Configuration Management Model (CMM). The paper concludes with a summary of key recommendations for the ITER RH system based on the experience of remote metrology at JET.

1. INTRODUCTION

The need to maximise the operational availability of fusion devices has always driven the enhancements in accuracy, flexibility and speed associated with the inspection techniques used at JET [1]. To this end, the remote installation of the ILW tiles, conduits and embedded diagnostics has necessitated the adoption of technologies from other industries for their use in conjunction with the JET RH system.

The JET RH system has evolved over decades of learning and is currently the most accomplished RH system of any fusion device in the world. Metrological surveys are now fully remote with no detriment to the accuracy; indeed it has yielded an improvement in many cases.

2. ILW AND THE EMBEDDED DIAGNOSTIC CONDUIT INSTALLATION

Spanning more than 5 octants on both the inner and outer walls, the embedded diagnostic conduit system is an integral part of the ILW (Fig.1). To allow installation, the system is first configured on a full-scale setting jig, constructed to match the coordinate data from the in-vessel surveys. Once the system is verified on the setting jig, the subcomponents are then deployed invessel using a bespoke suite of tooling.

3. SINGLE-CAMERA TARGETED PHOTOGRAMMETRY

The embedded diagnostic conduit photogrammetry survey was designed to globally survey all the in-vessel features interfacing with the conduits to sub-millimetric accuracy. A total of 75 target assemblies were deployed for the duration of the survey to ascertain the location and orientation of fixing bosses, datum points (for combining surveys with global coordinates), scale bars, arbitrary targets (for adding stability to the survey) as well as clearances and gaps through which the conduits are routed.

To minimise the duration of the in-vessel RH operation, a compromise was achieved between the accuracy required from the survey and the number of targets and camera shots implemented. Following the survey, Geodetic System's VSTARS software [2] generated an IGES file containing the results, allowing the Design Office to update the CATIA CMM relative to the best-fit of the datum measurements within.

The survey was conducted using an INCA II photogrammetry camera [3] cradled in a RH compatible frame. The functionality of the camera was controlled by inspection specialists in the RH control room. The required camera shots were formulated in Virtual Reality (VR) beforehand and simulated using VSTARS software, leaving the RH operators to align the camera's line of sight with pre-positioned virtual coordinates for each shot (Fig.2).

At their most basic, the RH compatible target assemblies consist of a precision made location feature that locates on the in-vessel part to be surveyed, a body that hosts one or more retro-reflective targets a known distance from the location interface, and RH features to facilitate handling, location, fixation, and recovery.

Wherever possible, the means of locating and fixing the target assembly in-vessel were based on the design of the new component (e.g. a tile) intended for that location. Besides reducing the design and development time, the targets served as a trial fit for the newcomponents – a feature which highlighted some important non-conformities in-vessel. Whilst this did delay the surveying activities, it provided an important early warning for the tile designers who were able to amend their designs before the tiles were scheduled for installation.

In the RH control room, inspection specialists checked the aspect ratio of targets in each shot, lens flare that could obstruct readings and natural reflections which could be misinterpreted by the software as retroreflective targets (where appropriate, targets were anodized black to mitigate this). Developments in design and technology offer the RH operators an opportunity to take greater ownership of the process hence simplifying the operational interface with the inspection specialist who can then take a more supervisory role.

As a platform for the camera, the relatively stable RH system facilitates exposure times of up to 435ms compared to hand held durations of just 24ms. Best-fit processing showed that the datum measurements were within 0.2mm of previous surveys, which is explained on the basis that the JET vessel is considered a dynamic structure. The accuracy with which an individual target assembly can be surveyed is approximately ±0.1mm (depending on the location mechanism). The conduits were designed to be configurable within limits based on the confidence of the previous CMM. Some of the invessel fixings were found to be outside the compliance afforded by the embedded diagnostic conduit design, prompting verification of target fitment with the stereophotogrammetry camera.

3. STEREOPHOTOGRAMMETRY

The necessity for a RH stereophotogrammetry system (Fig.4) was borne from the limitations of scaling from existing high resolution images. The system was devised to provide images with an improved level of resolution, untargeted local measurements accurate to ±1mm and basic verification of the single-camera photogrammetry surveys.

The system comprises a stiff, yet light-weight, RH frame, hosting a pair of Nikon D300 digital SLR cameras [4] oriented to measure between points at a depth of field of 600 - 1200mm. The cameras are connected via a USB hub, which presents the cameras as if they were connected directly to the computer in the RH control room. An umbilical leads to an interface box housing the media converter which is required for compatibility with the existing boom cables.

The cost, schedule and contamination levels prohibited the complex task of re-wiring the boom with ethernet cable hence the signal was transmitted via a spare coaxial cable, originally intended for lowresolution CCTV analogue signals. Using the media converter, the coaxial cable is able to transmit a reduced 10Mbits/s, alleviated to an extent by the cameras' onboard buffering (Fig.5). Each camera is controlled with an individual workstation running Nikon Camera Control Pro 2 software [5].

The design process between the system RO (Responsible Officer) and the RH team was challenging due to the flexibility afforded by the RH system. In the absence of a concise specification of the RH electrical supply requirements, it was not obvious how best to interface with the RH system. This is accountable to the fact that the JET RH system has been developed over many years and offers more flexibility than is practical to formalise in a specification document. In an attempt to converge on an increasingly generic interface, an onboard switch-mode power supply was used to ensure the stereo system had the same electrical supply requirements as other systems already in use.

Pending further testing, the system is currently used with a conservative level of confidence but potentially provides a means of measuring more accurately between selectable points, reducing the schedule and financial burden of manufacturing, calibrating and deploying dedicated target assemblies. The main limitation of the metrology system is the need to manually select points on the image from which to measure. Many of the components' shapes do not lend themselves to having obvious vertices from which to pick common points in the two images. Considering that all sharp edges are routinely removed to reduce the risk of beryllium handling, it becomes particularly challenging to interpret the image [6]. Future developments in the measurement software [7] may lead to an ability to select common edges and axes, reducing the reliance on sharp vertices.

Albeit a targetless system, the presence of photogrammetry target assemblies in-vessel at the time of the stereophotogrammetry survey provided a good selection of artefacts to verify calibration and transfer local coordinates to the global system. Accuracy of target body measurements ranged from ±0.4mm to ±0.7mm, depending on how well defined the images were. It was therefore obvious that the error induced from the manual selection of pixels is the most significant contributor to the overall accuracy and that best results require carefully staged photographs with vertices clearly defined. Where a similar system is envisaged in the future, it would be advisable to machine reference features (for all degrees of freedom) in new components, especially those with no defined features selectable from an image.

The system is sufficiently user-friendly for a trained RH operator to conduct both the in-vessel calibration and survey but reserving the measurements to be processed post-survey by an inspection specialist.

Similar to the targeted photogrammetry, the high resolution images from the stereo camera proved invaluable to both the diagnosis and prognosis of several installation challenges. Locations are traceable since all boom joint positions are logged to resolve an approximate position of the camera. Finally, The system hardware was relatively inexpensive at £5k, suggesting that it could be considered disposable for use in higher radiation environments.

4. GAP AND STEP MEASUREMENTS

The purpose of the GapGun [8] (Fig.6) is to measure the gaps and steps between selected ILW tiles to verify clearances and shadowing as required. The system operates on the principle of laser triangulation and is calibrated using a precision machined artefact before use.

The GapGun is a COTS component used mainly in the automotive and aerospace industries. The device was originally designed as a portable hand-held gap measuring probe but has been adapted for use on the JET RH system with the support of the vendor, Third Dimension. To achieve RH compatibility, the sensor was separated from the control box pendant via an umbilical. The control box plugs into the Mascot chest connection and transmits results, via a media converter, utilising the same coaxial cable used by the stereophotogrammetry camera.

Consequently, the trigger button has had to be rewired to bypass the control box and connect directly to the vendor’s bespoke software in the RH control room (which has since been made commercially available). This software was configured to output the Graphical User Interface (GUI) to the RH control room. To achieve vessel material compatibility, the COTS standoff, required to hold the gun the correct distance from the tile (Fig.7), had to be remade in polyethelene.

No inspection specialists are required during RH operations as results can be registered in a pre-prepared spreadsheet by the RH operators. Any measurements outside an acceptable tolerance are automatically highlighted prompting further inspection.

In comparison to manual operations, the RH system yielded faster results due to the stability of the Mascot hand. After taking 7 seconds to re-position, each reading took approximately 12 seconds to register, with accuracy unchanged. Mock-up trials showed a repeatability of 20μm.

CONCLUSIONS AND ITER RECOMMENDATIONS

As dynamic structures, tokamaks can never eliminate the need for dimensional inspection but complications due to legacy non-conformities are avoidable. Commensurate with modern quality systems, the extent of inspections would be reduced if robust quality procedures were maintained at the time of installation e.g. as-built/as-assembled drawings, inspection reports, life cycle documentation, accurate CMM etc.

The design process for integrating new and COTSbased systems with the RH system would be aided by the development of technical specifications for each RH electrical system [9], not to replace the RH engineer but to guide the design process.

With respect to the surveys, it is clearly advantageous to have two or more survey methods for verifying results and a greater level of confidence can be obtained if one of them delivers high resolution images. Experience suggests that flexible viewing angles and high resolution images will be essential to facilitate the assembly and maintenance of, as well as upgrades to, ITER. As

Bogusch [10] alludes, targeted photogrammetry will probably be used to link in-vessel features to the various datum systems during assembly of the vessel, the size of which advocates a remotely operated system. Furthermore, capitalising on the inspection opportunities prior to the machine becoming irradiated will maximise confidence in the CMM.

Finally, given the relative inflexibility of the ITER In-Vessel Viewing System (IVVS) [11, 12], a case could be made for a metrology system mounted from the In-Vessel Transporter (IVT) or Multi-Purpose Deployer (MPD). The implications of which would be a likely need for radiation tolerant high speed data links, easily replaceable optical fibres and a capacity for peltier cooled shielded enclosures. This balancing of flexibility, standardisation and future proofing of services is a challenge shared with the space industry, suggesting possible rewards from the investigation of SpaceWire and SpaceFibre systems [13, 14].

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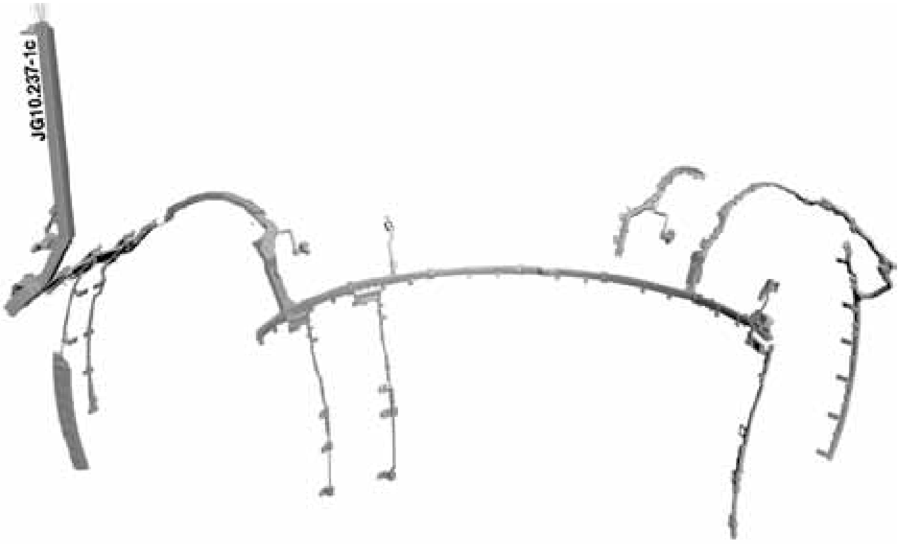

Figure 1: Embedded diagnostic conduit system

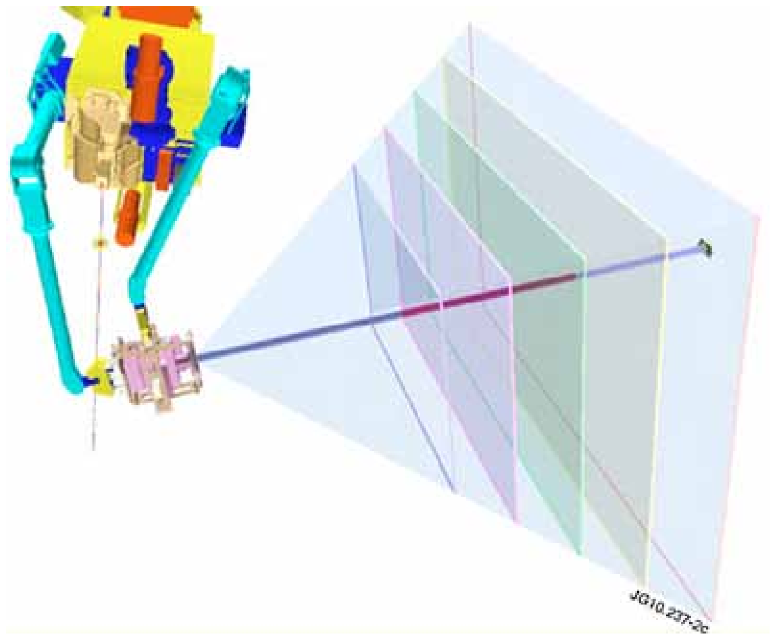

Figure 2: Mascot pointing INCA II at VR coordinate

Figure 3: Image from INCA II camera (435ms exposure)

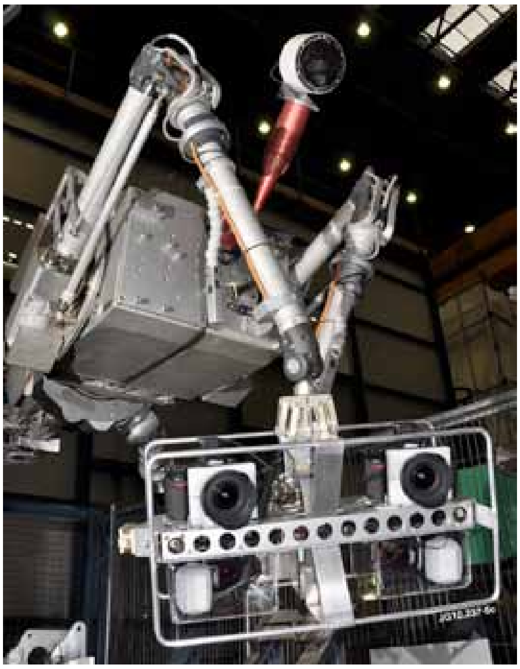

Figure 4: Stereophotogrammetry camera held by Mascot

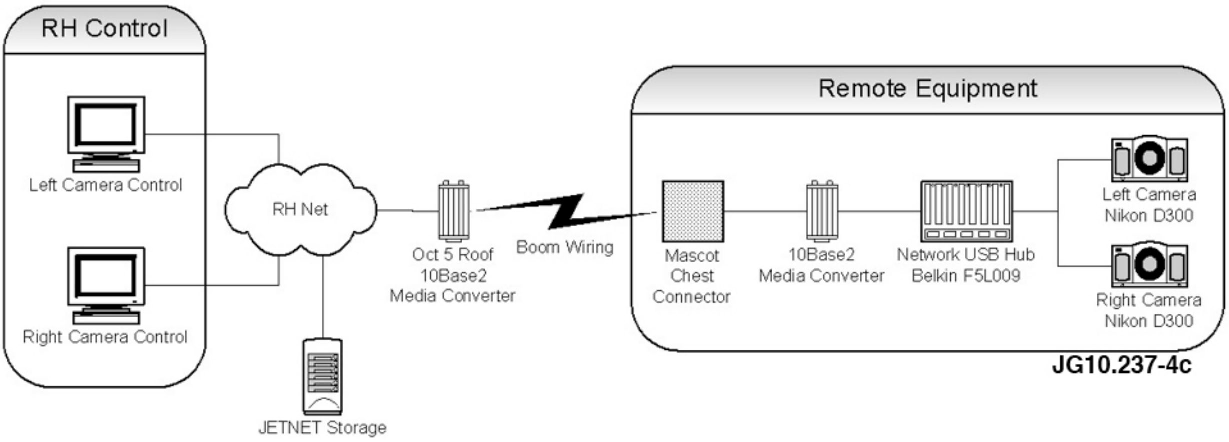

Figure 5: Schematic of stereophotogrammetry system

Figure 6: RH compatible GapGun sensor

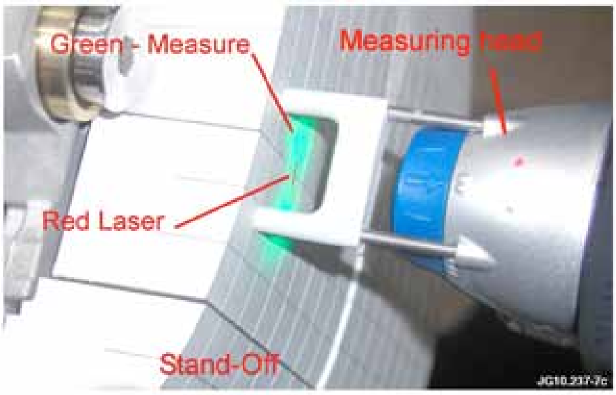

Figure 7: GapGun in action