25th International Congress on Modelling and Simulation, Darwin, NT, Australia, 9 to 14 July 2023
mssanz.org.au/modsim2023

Workspace and the Mixed Reality Lab: Where scientific workflows meet Industry 4.0

Damien Watkins, Matt Bolger and Zikai Zhang

CSIRO Data61, Clayton, Melbourne, Australia
Email: damien.watkins@data61.csiro.au

Abstract: The Computational Software Engineering and Visualisation team at CSIRO's Data61 has been developing two significant platforms over recent years: (1) Workspace, our Scientific Workflow & Application Development Framework and (2) the Mixed Reality Lab (MRL), our workspace-based testbed for the development of Digital Twin and Industry 4.0 applications.

Digital Twins are concerned with the modelling of real-world objects & process via computational models and the communication flows between the real-world objects & process and the models. Industry 4.0 is concerned with Digital Twins in the industrial domain. Digital Twins can be used to provide a number of potential benefits depending on the specific use case, such as:

- Ensuring that the real-world process execute in a safe manner
- Optimise the performance and reliability of the real-world process
- Inform and drive sustainability efforts (e.g. monitor and reduce waste)
- Enable new business models (e.g. "Just in time" inventory)

Digital Twins can be very complicated as they may need to incorporate hardware and software from different vendors while running on different operating systems/environments and over distributed computing backbones. Many of these requirements are common in the designing of workflow engines too.

As an Industry 4.0 testbed, the Mixed Reality Lab needs to deal with a wide variety of hardware and software, all of which needs to be connected via a common platform. In the MRL we choose to use Workspace as the common platform. Some of the functional areas of the MRL would include Calibration, Reconstruction and Visualisation. In this paper we look at some of the Calibration and Visualisation processes in the MRL and describe how these are implemented and integrated via workflows in Workspace. Given the paper's length, we only briefly touch on the requirements and their implementation. We discuss how we use Workspace workflows for everything ranging from controlling hardware, such as individual cameras through to a Kuka collaborative robot, up to visualisation of processes and results.

In this paper we look at the common requirements of camera calibration for all our different camera systems. Camera calibration is the process of calculating specific camera properties so it can be used in a system These properties can be intrinsic (internal properties of a camera – e.g. focal length, filed of view, resolution) or extrinsic (proprieties related to the network of cameras, such as its position and orientation in 3D – 3-dimensional space) relative to other cameras. Every camera system we use has a different calibration process, but they all share similarities, as we describe below.

We believe in the mantra "Variety is the spice of life", hence the ability to be able to integrate a wide variety of both hardware and software components is a strong advantage of our approach.

Keywords: *Scientific workflow systems, workspace, digital twins, mixed reality, Industry 4.0*

1. INTRODUCTION

The Computational Software Engineering and Visualisation (CSEV) team at CSIRO's Data61 have been developing two significant platforms over recent years. Workspace, our Scientific Workflow and Application Development Framework and the Mixed Reality Lab (MRL), our testbed for Workspace in the areas of Digital Twins and Industry 4.0 applications.

Workspace (Cleary et. al. 2017; 2020) has been under development at CSIRO since 2005 and a major goal of Workspace is to reduce the time taken to commercialise Research IP (Intellectual Property). Workspace sees most processes as workflows, with these workflows represented as platform independent XML files and these XML files can be executed via the Workspace runtime on multiple operating systems. There are versions of the Workspace runtime for Linux, macOS and Windows. Workspace has been used in a number of applications both within CSIRO and outside. Examples in the public domain would include:

- ArcWeld (Thomas et al. 2019)
- AeroDAQ (Sankaranarayanan et al. 2021)
- Dive Mechanic (Cohen et al. 2017; 2020)
- Digital Human/ErgoMechanic (Harrison et. al. 2021, Cohen 2021)
- Fractura (Kear et al. 2019)
- HelioSim (Potter et al. 2017)

The Mixed Reality Lab (Watkins, et. al. 2021) at CSIRO Clayton has been under development since 2017 and was initially opened in 2019. The MRL provides the opportunity for the CSEV team to experiment with designing and implementing Digital Twin and Industry 4.0 workflows and applications using Workspace. There are a number of processes involved in operating the MRL, such as Calibration, Reconstruction and Visualisation. Where possible we like to have multiple implementations of each process for a variety of reasons, such as characterisation and comparison (e.g., determining which implementation works best under which specific conditions – rarely, if ever, does one implementation perform best in all situations).

As mentioned in our last MODSIM paper (MODSIM 2021), the MRL (and Workspace) is continually under development and in this paper, we will talk about aspects regarding Calibration and Visualisation that we have been experimenting with over the last two years to identify commonalities, differences and challenges.

2. MIXED REALITY LAB

The MRL has a number of camera/vision systems which are used to measure and monitor the environment. When a camera is seen as a self-contained (simple) unit (e.g., we view Nikon and Ximea cameras in our MRL this way), we execute a single Workspace workflow on the PC that each individual camera is connected to. Usually, the differentiating value on each such workflow is only the Serial Number for the camera (everything else in the workflow is replicated across as many cameras/PCs combinations as needed). For camera systems such as the OptiTrack system, these configurations typically have a central controlling machine and application (e.g., Motive) to control all the cameras from a single PC. This single PC is where one or more Workspace workflows can be run to interface with the camera control software (e.g., Motive) to access the camera system as a whole. For the OptiTrack system the workflows use the NatNet SDK. In the MRL control workflows can be dispatched from a central server and run by the Workspace engine on any required PC.

The camera systems have many traits in common but there are a few variations. One common trait is the need for camera systems (and individual cameras) to be calibrated in the 3D space of the MRL. There are a number of techniques used in the MRL for camera calibration, these techniques vary from open systems to proprietary and a few are described in the following sections.

2.1. ChArUco

One calibration system is based on the ChArUco Camera Calibration functionality as implemented in OpenCV (https://opencv.org/). Our system uses flat (e.g. 2D) black and white target boards. In the MRL the ChArUco calibration process requires a couple of hundred poses of the board to be captured for a complete calibration. From these images the intrinsic and extrinsic of individual cameras can be calculated via distributed workflows accessing a shared file store. We have developed a couple of applications to assist with the process.

ChArUco calibration application

The ChArUco Calibration Application, which is a GUI application built over several Workspace workflows, guides users through the process of acquiring the calibration poses. Notable inputs to the application included specifics about the ChArUco board being used, such as the number of Horizontal and Vertical Squares, Marker Pattern and the Square Length and Width. The application has three separate tabs used during the pose/image acquisition process:

- "All Images" – shows all the images captured in the current/last pose
- "Detected Images" – shows all the images in the last pose in which the specified calibration board was detected
- "Accumulated Images" – shows the amalgamation of all the detected markers for all poses for each camera.

The basic objective is for all cameras to have a saturated number of detections in the "Accumulated Images" tab (see Figure 1). The "All images" and "Detected Images" are used to verify the process while capturing the poses/images, for example:

- Every camera should return an image in the "All images" tab regardless of whether it sees the calibration board or not.
- For every image in the "All images" tab where the calibration board is visible then an image and detections should be shown in the "Detected Images" tab.

These two tabs allow users to quickly ascertain if all cameras are working and if the calibration board is being successfully detected by the underlying workflows. The ChArUco Calibration Application has been used to calibrate systems with cameras from multiple vendors mixed in a single system, so this is a very flexible system from that perspective (e.g., no hardware vendor lock in).

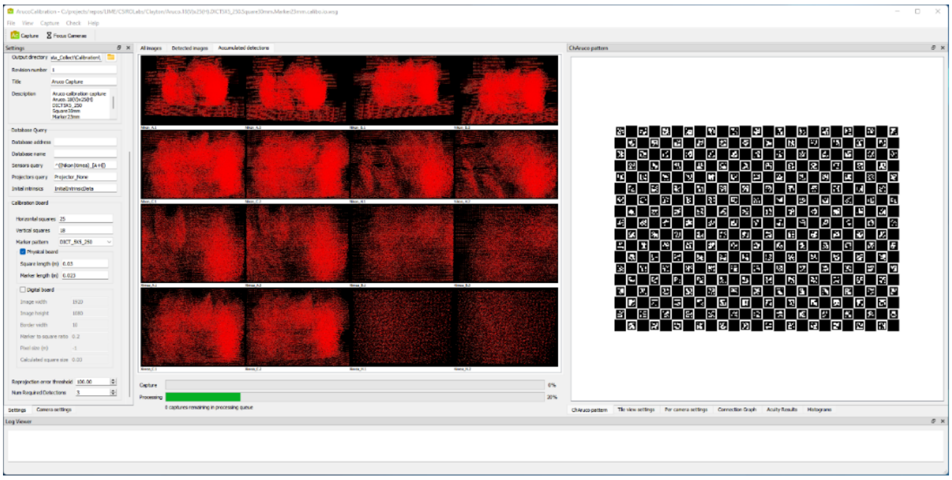

Figure 1. Screenshot of ChArUco Calibration Application after all poses have been collected. The "Accumulated detections" tab shows a heatmap for all cameras of marker detections across all poses.

2.2. Other systems: Australis, OptiTrack and MetraSCAN

Three proprietary calibration systems are used in the MRL: Australis, OptiTrack and MetraSCAN. The calibration process for Australis, OptiTrack and MetraSCAN will not be described in as much details as the ChArUco Calibration Application given the commonality of concepts, instead we provide an overview and note key differences.

Of the three proprietary calibration systems, Australis (www.photometrix.com.au/australis/) is most like the ChArUco system. With Australis the poses/images are taken with our own workflows using cameras from different vendors and saved in a subdirectory file structure that matches the Australis project format. An Australis project file is then generated by running a Workspace workflow and which is then opened in the Australis application. From this point the Australis calibration system essentially executes as per the Australis manual. The Australis Calibration board is decorated with a random number of pre-printed targets. Targets can be reflective or passive. Targets follow a pattern and two targets with the same pattern cannot be fitted to the same board. Unlike the ChArUco Calibration Board (which is 2D) the Australis calibration board is 3D. The Australis calibration system uses a predefined scale bar which must be visual in at least one pose (however we have attached it to the Australis Calibration board, so it appears in all poses.) Given the 3D board and scale bar, far fewer poses are needed to achieve the same results as the ChArUco based process. The Australis application requires a dongle to run and is therefore run on a single machine in the MRL.

Recently OptiTrack and MetraSCAN 3D systems have been acquired. Their 3D calibration process uses specific calibration hardware supplied with the units, (i.e., these systems both use a type of wand which also acts as a scale bar). For OptiTrack the wand is manually waved around in front of the cameras. The OptiTrack calibration application provides a display which logically resembles the "Detected Images tab" in the ChArUco Calibration application. Again, the goal is to obtain good coverage of the FOV (Field of View) of each camera. The MetraSCAN 3D system also uses a wand, however the calibration application directs the user to move through the space/MRL and hold the wand at different distances and angles to calibrate the C-Track. The handheld MetraScan scanner is next calibrated, again by following placement images in the MetraSCAN application. As infrared cameras are used in both the OptiTrack and MetraSCAN systems, targets need to be reflective and well illuminated.

3. CHALLENGES

3.1. Calibration drift

Cameras, and therefore their calibrations (e.g. extrinsic values), tend to drift over time. This can be because of environmental aspects such as ambient temperature changes or the quality of their fixtures and fittings through to accidental impacts or even up to seismological events. The bottom line is that no system can be calibrated once and forgotten about. A first step in managing this is to develop a workflow that measures the accuracy of the current calibration and displays the results to the lab operators. A Workspace workflow has been developed that takes a calibration and provides an assessment of the quality. Various more complex techniques for assessing this quality are used but, at its most basic, this can be based on looking at average reprojection error of common observations (board corners) across the multiple cameras. The workflow produces a table such as the one in Figure 2 which looks at both camera pair-wise assessments as well as overall assessment of each camera against the full network.

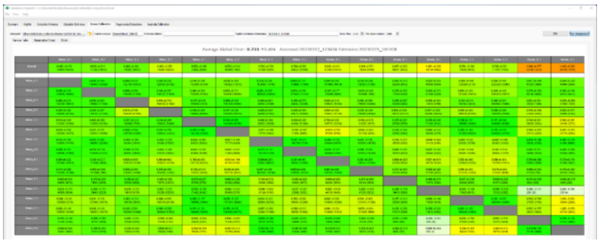

Figure 2. Screenshot of calibration assessment for a ChArUco calibration

However, it can be noticed in Figure 3 that on subsequent days the accuracy has changed. Since this was on a single camera it is more likely to be an accidental impact on a camera (the camera in question being identified by the intersection of the red vertical and horizontal lines).

Figure 3. Screenshot of Assessment table after apparent camera impact

3.2. Calibration adjustment

The calibration adjustment workflow is based on some assumptions: one is the Extrinsics is more likely to drift than Intrinsics, the other is that usually drifted cameras are still roughly located where they were in the last verified calibration. Therefore, the most recent verified calibration is used as a prior to perform calibration adjustments in the Workspace workflow. We can then assess both the prior and the adjusted calibration against a captured dataset.

The components for assessing a given calibration and adjusting a prior calibration extrinsics are provided in Workspace as nested workflows using Ceres and OpenCV plugins. These workflow components can easily be used to build up workflows with minor effort. For example, a workflow runs nightly in the MRL to perform calibration adjustments of both the last verified calibration and the last adjusted calibration, assessing the prior and the adjusted respectively and publishing the assessment results to show any trends of the calibration quality over time.

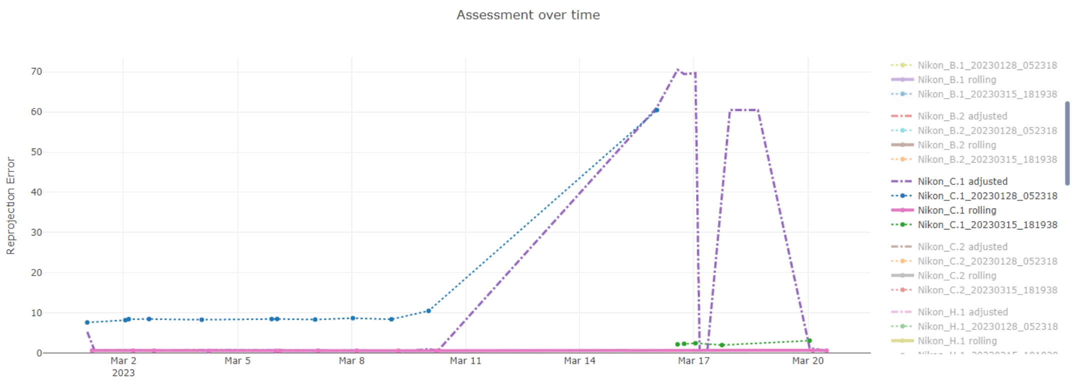

Figure 4. Calibration assessment report of Nikon_C.1 camera over time

3.3. Automation of calibration images collection

A recent addition to the MRL is a Kuka OmniMove Platform with IIWA Cobotic arm. Recently we have started to automate the collection process using the Kuka Platform. While a projected pattern method could help to automate the calibration process, the quality of the observations has not been as good as using a printed physical calibration board. The integration of a robotic arm holding a calibration board improves the accuracy and quality of automated calibration adjustment while reducing the amount of human activity.

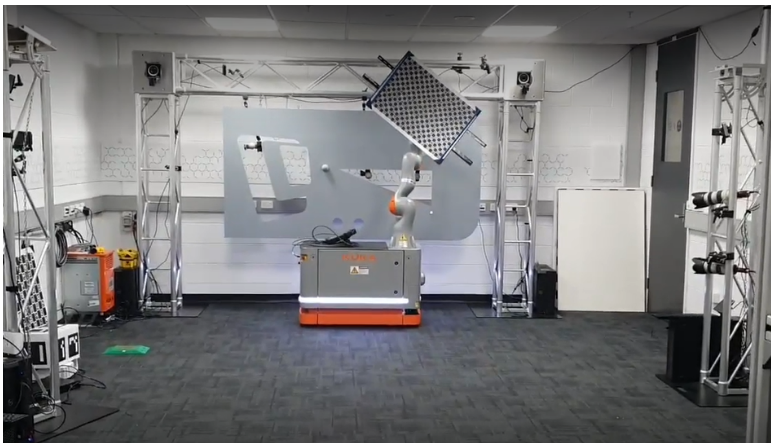

Figure 5. Robot-assisted calibration image capture

3.4. Mixed reality visualisation of calibration data and results

Workspace's 3D visualisation capabilities include a flexible pipeline to support visualising workflow results using Virtual and Augment Reality (AR) headsets without the need to develop custom applications for each project use case. In Figure 6 below we show images captured from a Microsoft HoloLens AR headset which is running the Workspace Inter-Process-Viz (IPV) client to stream visualisation results from the Workspace workflow. This workflow is executing the automated, robot assisted, calibration collection and assessment process. The AR visualisation from Workspace is world locked to the physical space of the lab using other QR code landmarks on the lab walls allowing the team members to look at 3D spatial results in their real-world location. The small spheres in the image represent the detected marker corners from multiple poses of the robot and are colour coded based on the assessed reprojection error of these markers across the camera network. Workspace allows the team to rapidly develop and customise a visualisation in the Workspace editor running on one of the lab PCs and then make live changes that are instantly reflected in the AR headset scene. Examples include changing the property or range used for colour coding markers or enabling and disabling different parts of the visualisation.

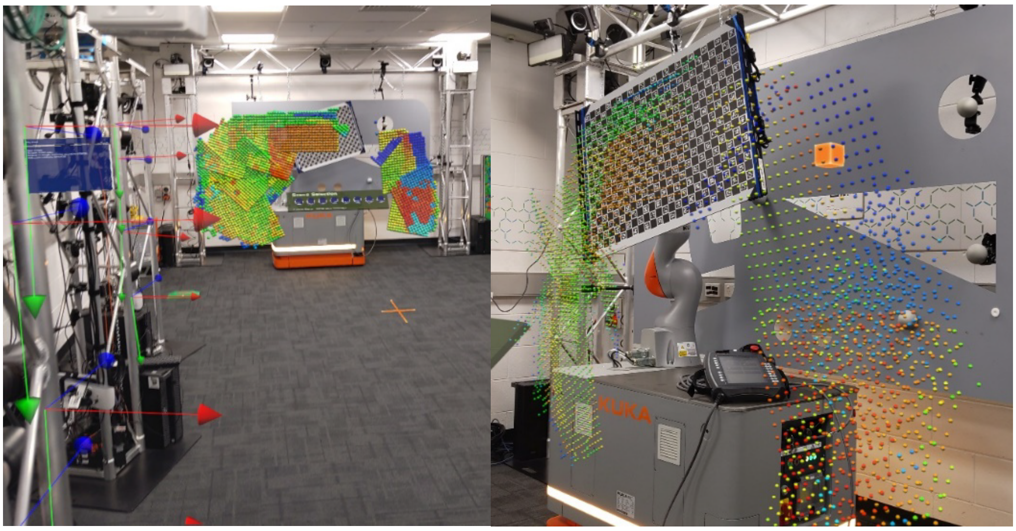

Figure 6. Mixed reality visualisation of reprojection error for detected ChArUco markers

With Workspace's plugin architecture and library of existing plugins, the team can quickly experiment with data processing, analysis and visualisation pipelines that draw on internally developed algorithms and capabilities and leverage popular open-source libraries such as OpenCV, PCL and VTK. These workflows often include distributed communication with Workspace workflows running on other machines in the lab for data acquisition and control of components such as sensors, robots and projectors. The resulting 2D images, charts and complete 3D scenes generated from these, often complex, workflows can then be easily presented as part of the mixed reality view in the lab to help investigate and communicate source and intermediate data and final results. Figure 7 below shows the Workspace workflow for visualizing the current camera calibration network and a post-analysis 3D reconstruction result. Figure 8 then presents a view of this through the HoloLens AR headset showing the camera transform, view frustum and the last captured image from the many camera types in the lab.

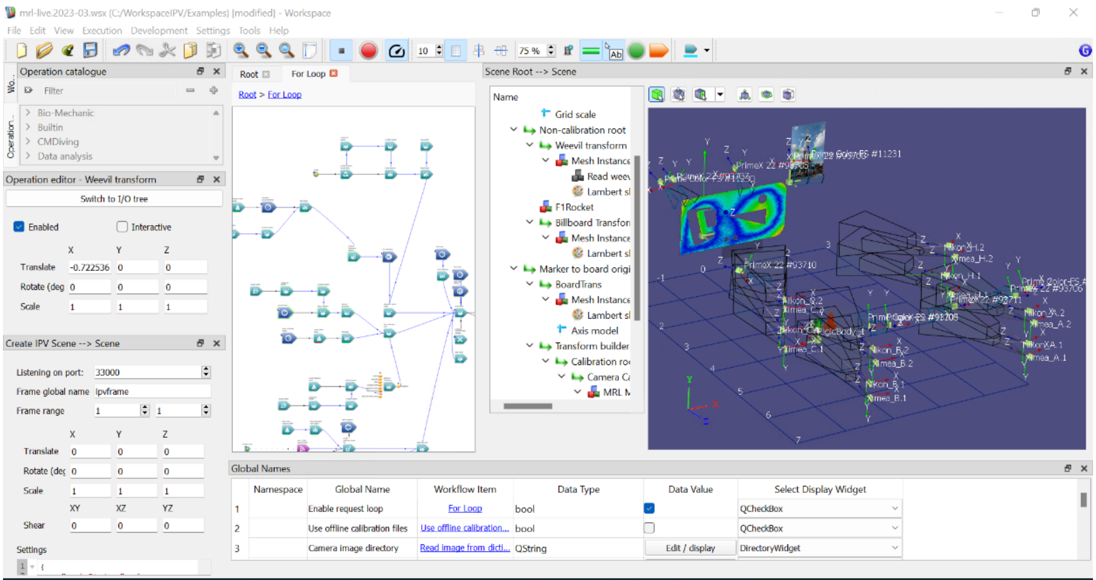

Figure 7. Workspace workflow of calibrated camera network and 3d reconstruction results

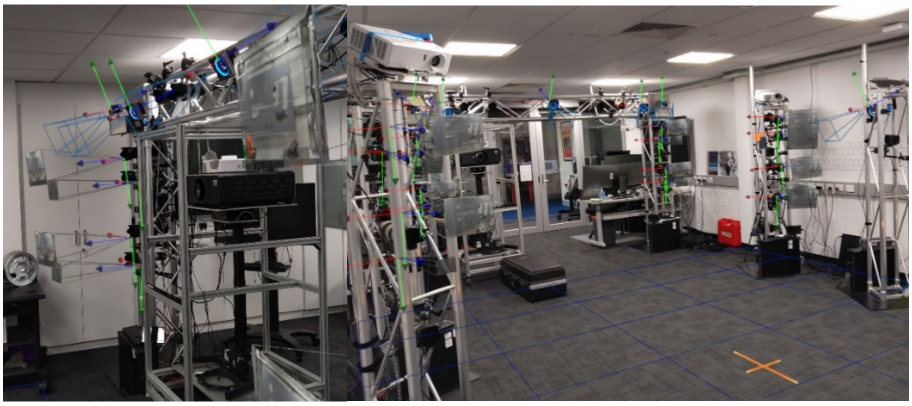

Figure 8. Mixed reality visualisation of combined calibration solution for Nikon, Ximea and OptiTrack cameras

4. DISCUSSION AND CONCLUSION

In this paper we have shown how we are able to represent devices, processes and functionality in MRL as Workspace workflows. Workflows can be distributed to remote PCs to control devices, can be sent to servers to do intensive processing and can visualise results – either on screens or in AR headsets. We continue to find new and interesting systems and identify benefits and challenges integrating hardware and software coming from multiple groups into a coherent "Digital Twins"/"Industry 4.0" system. One route taken by others is to limit the hardware and software to a preconfigured design and to eliminate interaction with other components to simplify management. Unfortunately, the real world does not have such limitations and allows for a large variety of implementations. For this reason, we see platforms such as Workspace as a significant advantage in allowing integration of multiple often closed systems into a single highly usable environment that can adapt quickly to new or changing use cases and changing hardware option.

REFERENCES

Cleary, Paul W. Thomas, David. Hetherton, Lachlan, Bolger, Matt, Hilton, James E., Watkins, Damien, 2020, Workspace: A workflow platform for supporting development and deployment of modelling and simulation, Mathematics and Computers in Simulation, Volume 175, 2020, Pages 25-61, ISSN 0378-4754.

Cleary, Paul W. Watkins, Damien, Hetherton, Lachlan, Bolger, Matt, Thomas, David, 2017, Opportunities for workflow tools to improve translation of research into impact presented at 22nd International Congress on Modelling and Simulation (MODSIM) 2017.

Cohen, Raymond C. Z., Harrison, Simon M., Cleary, Paul W., Bolger, Matt, 2017, Dive Mechanic: Bringing 3D virtual experimentation to elite level diving using the Workspace workflow engine presented at 22nd International Congress on Modelling and Simulation (MODSIM) 2017.

Cohen, Raymond C. Z., Harrison, Simon M., Cleary, Paul. W., 2020, Dive Mechanic: Bringing 3D virtual experimentation using biomechanical modelling to elite level diving with the Workspace workflow engine. Mathematics and Computers in Simulation 175, 202–217.

Cohen, R.C.Z. and Harrison, S.M., 2021, Ergomechanic: A markerless motion capture and ergonomic assessment tool developed using the Workspace workflow engine, presented at 24th International Congress on Modelling and Simulation (MODSIM) 2021.

Harrison, S.M. and Cohen, R.C.Z. 2021, Mechanical digital twinning of the human body in the workplace for reduced injury risk and improved health, presented at 24th International Congress on Modelling and Simulation (MODSIM) 2021.

James Kear, Dane Kasperczyk, Lachlan Hetherton, Dang Quan Nguyen, Chris Rucinski, Abbas Movassagh, Saeed Salimzadeh, Xi Zhang, 2019, Fractura – Common modelling platform for multiple hydraulic fracture simulators presented at 23rd International Congress on Modelling and Simulation (MODSIM) 2019.

Sankaranarayanan, N. and Humphries, R. 2021, AeroDAQ: A Workspace based application, presented at 24th International Congress on Modelling and Simulation (MODSIM) 2021.

Thomas, David G., Murphy, Anthony B., Chen, Fiona F., Xiang, Junting, Feng, Yuqing, 2019, ArcWeld: A case study of the extensibility of software applications built using Workspace architecture presented at 23rd International Congress on Modelling and Simulation (MODSIM) 2019.

Watkins, Damien, Bolger, Matt, Hetherton, Lachlan, Zhang, Zikai, Xie, Ping, Harrison, and Cohen, Raymond C. Z, 2021, Using Workspace to implement Digital Twins in the Mixed Reality Lab, presented at 24th International Congress on Modelling and Simulation (MODSIM) 2021.