FINAL SCRIPT: APPROVED FOR FILMING

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Title: Automatic Laser-Based Geometry Capture for Finite Element Analysis of Weld Beads

Authors and Affiliations:
Robin C. Laurence[1,2], Jinjiang Li[1], Zeyuan Miao[1], William Smith[1], Matthew J. Roy[1,2], Lee Margetts[1]

[1]Department of Mechanical and Aerospace Engineering, University of Manchester
[2]Henry Royce Institute, University of Manchester

Corresponding Authors:
Robin C. Laurence robin.laurence@manchester.ac.uk

Email Addresses for All Authors:
Jinjiang Li jinjiang.li@manchester.ac.uk
Zeyuan Miao zeyuan.miao@manchester.ac.uk
William Smith william.smith-7@manchester.ac.uk
Matthew J. Roy matthew.roy@manchester.ac.uk
Lee Margetts Lee.Margetts@manchester.ac.uk
Robin C. Laurence robin.laurence@manchester.ac.uk

Author Questionnaire

1. Microscopy: Does your protocol require the use of a dissecting or stereomicroscope for performing a complex dissection, microinjection technique, or something similar? **No**

2. Software: Does the part of your protocol being filmed include step-by-step descriptions of software usage? **Yes**

3. Filming location: Will the filming need to take place in multiple locations? **No**

Current Protocol Length
Number of Steps: 25
Number of Shots: 44 (31 SC)

Introduction

Videographer: Obtain headshots for all authors available at the filming location.

Videographer's NOTE: There were lighting issues for interviews

1.1. **Robin C. Laurence:** Automated welding is widely used and capable of creating uniform and reproduceable welds. It, however, currently lacks the ability for adaption during a multi pass welding process, something which would happen during manual welding by a skilled technician.

1.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 2.3.1*

What advantage does your protocol offer compared to other techniques?

1.2. **Robin C. Laurence:** Our protocol allows the progress to be monitored without causing delays; unlike manual capture of the weld geometry using physical gauges. It also produces a digital record of the deposition which can be used for future analysis.

1.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 2.5.1*

What significant findings have you established in your field?

1.3. **Jinjiang Li:** This protocol is enabled by MetaWAAM which is the digital twin of the welding cell developed at our University. The digital twin allows the recording and playback in a digital space of not just the build geometry but also all robot instructions, actual robot movements and camera footage of the welding cell and the local melt pool.

1.3.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 3.2.1*

What are the current experimental challenges?

1.4. **Jinjiang Li:** The laser scanner needs to be calibrated to correct for any skew or tilt between it and the build plate. As part of this calibration the laser scanner data is brought into the coordinate system of the welding robot.

1.4.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 4.2.1*

How will your findings advance research in your field?

1.5. **Zeyuan Miao:** Rapid capture of the weld geometry can facilitate decision making between passes, possibly enhanced through machine learning and allow finite element models to be populated with true deposition geometry.

1.5.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 5.2.1*

Protocol

2. Instrument Calibration Procedure

Demonstrators: Robin Laurence and Jinjiang Li

2.1. To begin, place the calibration component inside the welding cell in the same orientation relative to the origin in the coordinate measuring machine **[1]**.

2.1.1. WIDE: Talent placing the calibration component inside the welding cell.

2.2. Set up the scan of the calibration component **[1]** using the laser scanner system **[2]** and record the scan output in a coordinate file containing X, Y, and Z values **[3]**.

2.2.1. Talent handling the robot control panel. **Videographer's NOTE**: Shot 2.2.1 is a wide shot. Take 1 has everything in focus. The takes after this have a rack focus from the tablet to the robot. The best shots of this shot are Takes 1 and 4 in my opinion.

2.2.2. Shot of scanner approaching the starting point. **Videographer's NOTE:** Take 2 should be used where laser is clearly visible

2.2.3. Shot of Robot scanning in motion and one of the operator instigating the automated scan. *Videographer: Please shoot over the shoulder of the talent such that the tablet operation and the robot are both visible.*

2.3. Measure each fiducial sphere, using the laser scanner **[1]**. Scan across each sphere to measure the calibration component **[2]**. Truncate the line scan data by excluding points originating from the substrate using circular masks in X and Y around the known positions and applying thresholds in Z **[3]**. Use the filtered point set to perform a least-squares sphere fitting and determine the central coordinates **[4]**.

2.3.1. SCREEN: 68654_screenshot_1.mkv 00:14-00:21.

2.3.2. SCREEN: 68654_screenshot_1.mkv 0:21-0:28.

2.3.3. SCREEN: 68654_screenshot_1.mkv 0:28-0:31.

2.3.4. SCREEN: 68654_screenshot_1.mkv 0:31-00:45.

2.4. Now, locate the calibration component using the welding robot equipped with a metallic tip of known dimensions **[1]**. Using the touch sense routine , bring the tip into contact with the surface of each fiducial sphere at several locations **[2]**. Allow the low-voltage circuit to complete upon contact and record the robot's position through the system software **[3]**.

2.4.1. Shot of the machine showing the robot metallic tip coming close to a fiducial sphere. **Videographer's NOTE:** Shot was modified

2.4.2. Close-up of the metallic tip contacting various points on the sphere's surface.

2.4.3. Display the touch sense signal on the robot.

2.5. Then, place the substrate or parent material that will receive the deposition into the welding cell **[1]**.

2.5.1. Talent placing the substrate or parent material securely inside the welding cell. **Videographer's NOTE:** Shot 2.5.2 is an extra shot. This essentially is a closer shot of 2.5.1

2.6. Next, initiate a weld pass using the welding robot to deposit a bead of material along the substrate surface **[1]**.

2.6.1. LAB MEDIA: Screenshot 2.avi_h264 00:11-00:20. **NOTE:** Videographer also has shot this scene, but don't use that. Use the one author has provided as lab media

3. Scanning the Bead and Generating Finite Element (FE) Geometry

3.1. Program the scanning robot to follow a path aligned with the bead location **[1]**. For simple linear beads, use the same start and end points as the welding robot **[2]** and scan the entire plate area with the scanning robot for enhanced coverage **[3]**.

3.1.1. Shot of the scanning robot moving to the start and end.

3.1.2. Shot of the robot moving.

3.1.3. Show a close-up of full plate scan path being loaded and executed by the scanning robot.

3.2. Take measurements while moving the scanner over the workpiece. Record the start and end points of the scanning path **[1]**, the movement speed of the robot **[2]**, and the acquisition frequency **[3]**. Confirm that the frequency corresponds to a spatial interval no smaller than the minimum element size planned for the finite element analysis **[4]**.

3.2.1. ~~Shot of the robot moving along the surface of the workpiece during scanning~~. **NOTE**: Delete the shot, VO merged

3.2.2. SCREEN: 68654_screenshot_3.mkv. 00:45-00:52

3.2.3. SCREEN: 68654_screenshot_3.mkv. 0:56-01:04

3.2.4. SCREEN: 68654_screenshot_4.mkv. 0:00-0:05

3.2.5. SCREEN: 68654_screenshot_4.mkv. 0:06-00:14.

3.3. Fit the scanned bead profile with an appropriate analytical function using Python code. For single bead depositions, use a parabolic function for curve fitting **[1]**.

3.3.1. SCREEN: 68654_screenshot_5.mkv 0:28-0:39 and 00:42-00:45.

3.4. Apply the same affine transformation matrix to the laser scan data as used during calibration **[1]**.

3.4.1. SCREEN: 68654_screenshot_6.mkv.

3.5. Crop the scan data to a region that covers the bead and includes a margin around it **[1]**. Remove any scanning artifacts caused by reflections using height-based filters **[2]**.

3.5.1. SCREEN: 68654_screenshot_7.mkv.

3.5.2. SCREEN: 68654_screenshot_8.mkv.

3.6. Then, flatten the local region of the plate in the cropped scan by solving for the plate normal **[1]** and apply a rotation matrix to align the plate normal with the vertical axis **[2]**.

3.6.1. SCREEN: 68654_screenshot_9.mkv 00:03-00:18.

3.6.2. SCREEN: 68654_screenshot_10.mkv 00:02-00:10.

3.7. Rotate the bead so that it aligns with the y-axis to simplify further processing **[1]**.

3.7.1. SCREEN: 68654_screenshot_11.mkv 0:08-00:13.

3.8. Detect the bead orientation by applying a height filter just above the base plate level **[1]** and fit the resulting data with a first-order polynomial to generate a vector representing the bead direction. If the bead is not straight, divide it into smaller segments that approximate straight lines **[2]**.

3.8.1. SCREEN: 68654_screenshot_12.mkv 00:05-00:10.

3.8.2. SCREEN: 68654_screenshot_12.mkv 00:11-00:17.

3.9. Now, crop the rotated section to remove excess plate area while retaining approximately 5 millimeters of material on either side of the bead **[1]**.

3.9.1. SCREEN: 68654_screenshot_13.mkv 00:00-00:04.

3.10. Choose the central region of the bead for fitting and execute a parabolic curve fit to the cross-section of the data at this location **[1]**.

3.10.1. SCREEN: 68654_screenshot_14.mkv 00:00-00:17.

3.11. Then, using the fitted parabolic curve, determine the bead's lateral extents by evaluating the curve at the X coordinates where the bead meets the base plate at its maximum height **[1]**.

3.11.1. SCREEN: 68654_screenshot_14.mkv. Freeze frame at 00:17 *Video editor: Highlight the black line cutting at the center of the structure*.

3.12. Next, evaluate the Y coordinates which indicate the extents of the bead by using similar height thresholding techniques **[1]**.

3.12.1. SCREEN: 68654_screenshot_14.mkv. Freeze frame at 00:17 and *Video editor: Highlight the top right edge of the structure*

3.13. Create termination profiles at both ends of the bead using the same parabolic shape, transposed into the X-Y plane **[1]**.

3.13.1. SCREEN: 68654_screenshot_14.mkv. Freeze frame at 00:17 and *Video editor: Highlight the top boundary of the structure*.

3.14. Now, calculate the full outline of the bead by evaluating all parabolas at multiple X and Y coordinates covering the bead's entire span **[1]**.

3.14.1. SCREEN: 68654_screenshot_14.mkv. 00:17-00:24.

3.15. Then, add the base substrate geometry by specifying its actual extents or using predefined dimensions **[1]**.

SCREEN: 68654_screenshot_15.mkv 00:00-00:03, *Video editor: highlight the W=30.000mm h=10.000mm, t=1.00.mm under FreeCAD section*.

3.16. Then, use meshing tools in FreeCAD *(free-cad)* to convert the set of parabolic cross-sections into a single 3D solid geometry **[1]**. This surface should be suitable for import into a finite element analysis environment **[2]**.

3.16.1. SCREEN: 68654_screenshot_15.mkv 0:04-0:10 and 01:10-01:17.

3.16.2. SCREEN: 68654_screenshot_16.mkv 00:00-00:10.

3.17. Translate the outline points into the original welding robot coordinate system. First, reset the bead to the origin of a new coordinate system, then apply the transformation to restore its position in the original frame **[1]**.

3.17.1. SCREEN: 68654_screenshot_17.mkv 0:00-0:04 and 0:55-01:12.

3.18. Use macros to export the bead and substrate as STL *(S-T-L)* and STEP *(Step)* files using the previously calculated geometry points **[1]**.

3.18.1. SCREEN: 68654_screenshot_18.mkv . 00:05-00:12

3.19. Finally, export the complete geometry into a file format appropriate for finite element analysis, such as the .inp *(I-N-P)* format **[1]**. Optionally, use the Netgen mesh FEM *(F-E-M)* tool in FreeCAD to create the mesh using moderate fineness, with a maximum element size of 0.5 millimeters and minimum of 0.1 millimeters **[2]**.

3.19.1. SCREEN: 68654_screenshot_18.mkv. 00:12-00:13

3.19.2. SCREEN: 68654_screenshot_19.mkv 00:20-00:27.

Results

4. Results

4.1. The transformation matrix applied to the fiducial sphere locations resulted in visibly distinct point sets between the coordinate systems **[1]**.

4.1.1. LAB MEDIA: Figure 14.

4.2. The measured radii of the fiducial spheres using the laser scanner showed consistent underestimation **[1]** compared to edge finding and coordinate measuring machine techniques **[2]**.

4.2.1. LAB MEDIA: Table 2. *Video editor: Highlight the column "Radius as measured with laser scanner"*

4.2.2. LAB MEDIA: Table 2. *Video editor: Highlight the columns "Radius as measured with edge finding" and "Radius measured with CMM".*

4.3. The positional error of the laser scanner in determining distances between fiducial spheres ranged from 1.30 millimeters to 2.05 millimeters **[1]**, while both CMM and electronic edge-finding errors remained below 0.1 millimeters **[2]**.

4.3.1. LAB MEDIA: Table 2. *Video editor: Highlight the values in the column "Distance between fiducial sphere centres Laser robot to welding robot*"

4.3.2. LAB MEDIA: Table 2. *Video editor: Highlight the values in the column "Distance between fiducial sphere centres CMM to welding robot*".

4.4. The final meshed full weld bead geometry was successfully imported into the finite element analysis software **[1]**.

4.4.1. LAB MEDIA: Figure 15.

1. calibration

Pronunciation link:
https://www.merriam-webster.com/dictionary/calibration Encyclopedia Britannica+10Merriam-

Webster+10WordReference+10
IPA: /ˌkæl.əˈbreɪ.ʃən/
Phonetic spelling: kal-ə-BRAY-shun

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2. fiducial

Pronunciation link:
https://www.merriam-webster.com/dictionary/fiducial YouTube+11Merriam-Webster+11WordReference+11
IPA: /fəˈduː.ʃəl/
Phonetic spelling: fi-DOO-shəl

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3. parabolic

Pronunciation link:
https://www.merriam-webster.com/dictionary/parabolic Merriam-Webster+14Merriam-Webster+14Merriam-Webster+14
IPA: /ˌper.əˈbɑː.lɪk/
Phonetic spelling: per-uh-BAH-lik

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4. affine

Pronunciation link:
https://www.merriam-webster.com/dictionary/affine How To Pronounce+7Merriam-Webster+7YouTube+7
IPA: /əˈfaɪn/
Phonetic spelling: uh-FINE

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5. meshing

Pronunciation link:
https://www.merriam-webster.com/dictionary/meshing Merriam-Webster+15Merriam-Webster+15Oxford English Dictionary+15
IPA: /ˈmɛʃ.ɪŋ/
Phonetic spelling: MESH-ing