Inline measurement of serial manipulator robots for 3D Concrete Printing

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1. Problem

Geometric accuracy of parts is an increasingly important issue in 3D Concrete Printing. The inherent robot errors, especially in an uncontrolled environment, make consistent and accurate production challenging.

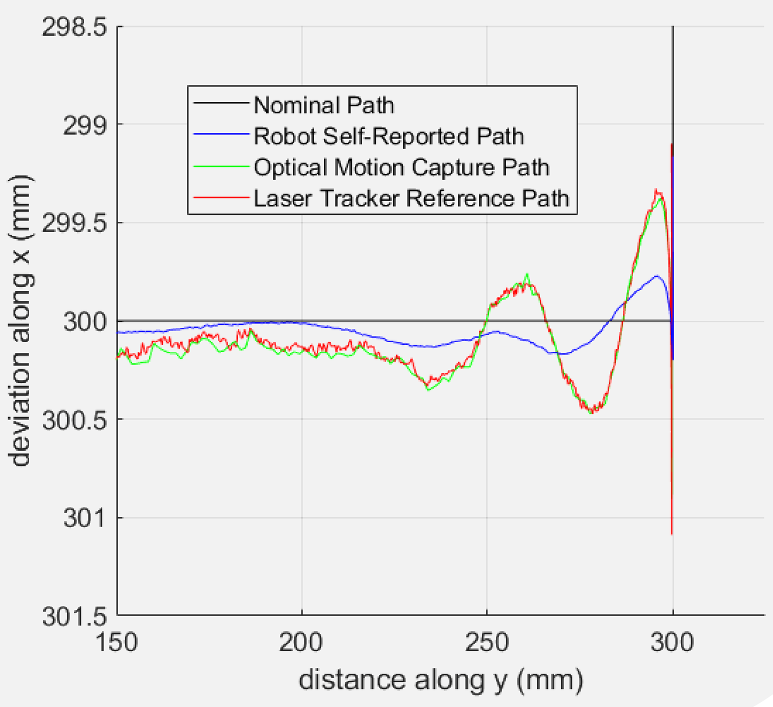
The COHESION Pavilion (right) is made from 47 unique, freeform panels each printed off-site, transported, and assembled on-site.

2. Nozzle Measurement

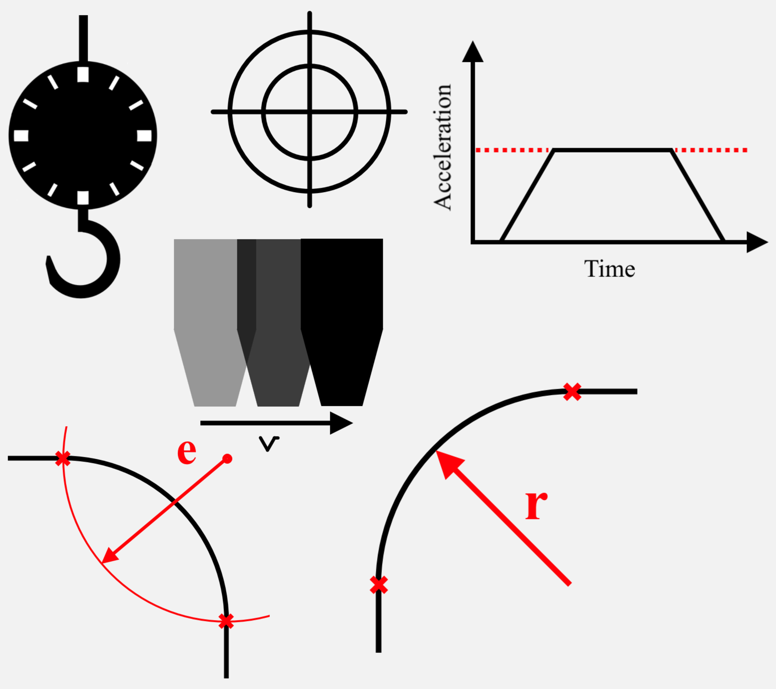
To measure the nozzle during printing, the Optical Motion Capture system, Optitrack, is chosen. The robot path is measured around a corner motion. The figure, and table below shows the nominal nozzle path, the robot's own model, and the Optitrack system, as compared against a high-accuracy reference system (AT960 Laser Tracker, courtesy of the Manufacturing Technology Center).

Measurement System	Max Deviation Error (mm)	Mean Deviation Error (mm)
Laser Tracker Reference	0	0
None, Assume Nominal Path	2.31	0.84
Robot Self-Reported Position	2.13	0.82
Optical Motion Capture	1.33	0.29

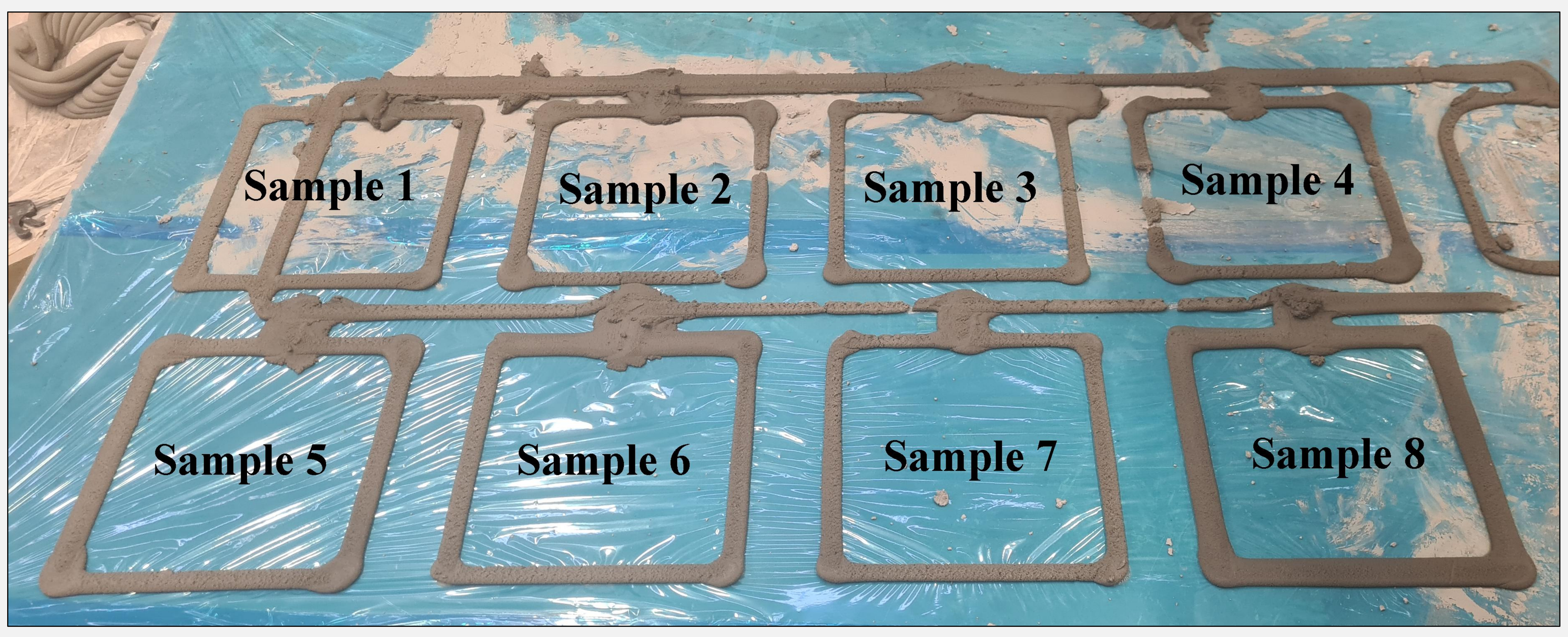
The data shows that Optitrack agrees reasonably well with the reference laser tracker, with mean deviation errors of 0.29 mm. Furthermore, the robotic system can overshoot the corner point by about 1 mm, and can dwell in the corner region due to the disturbed motion. Further work tests the effect of changing control parameters on robotic motion performance.



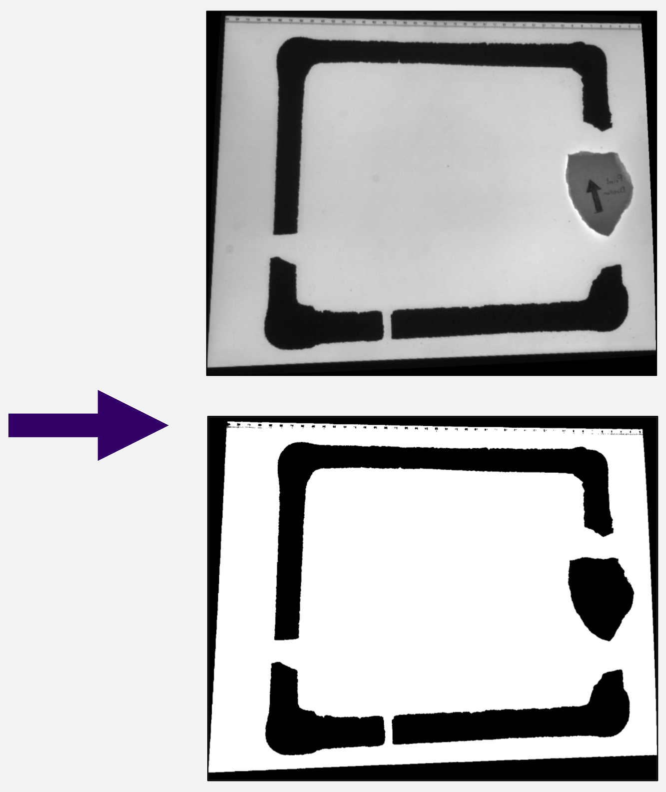
3. Printing Test Samples



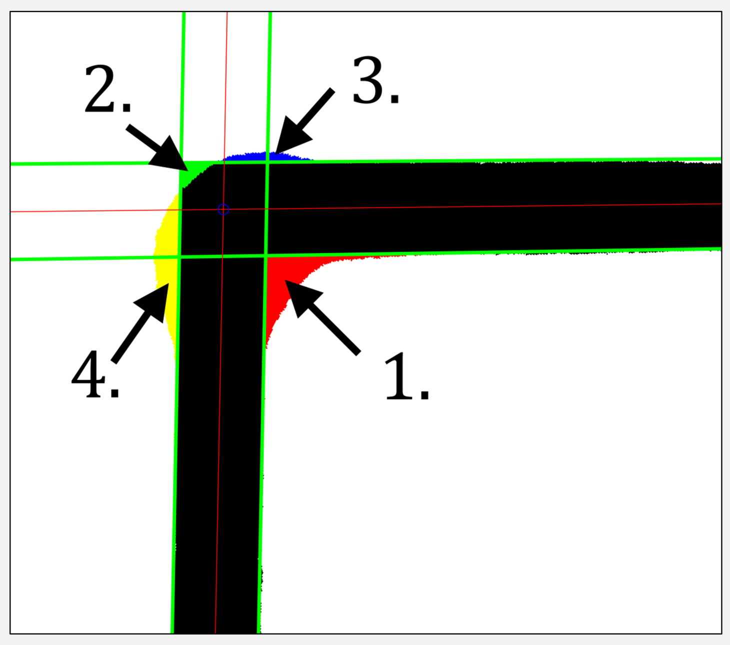
1575 samples are measured across six different motion settings, including the nozzle speed, printing region, acceleration limits, and cornering radius. Results show a huge range of path outcomes, with the worst case taking 10% longer to print sample parts, and large corner dwell times in excess of 2 seconds. Of these samples, 8 are chosen which represent the range of path variability, and therefore print error. These are printed and shown below.



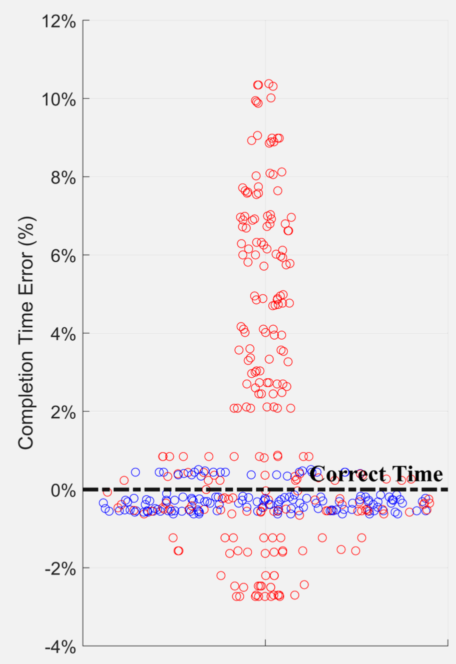
4. Imaging Samples



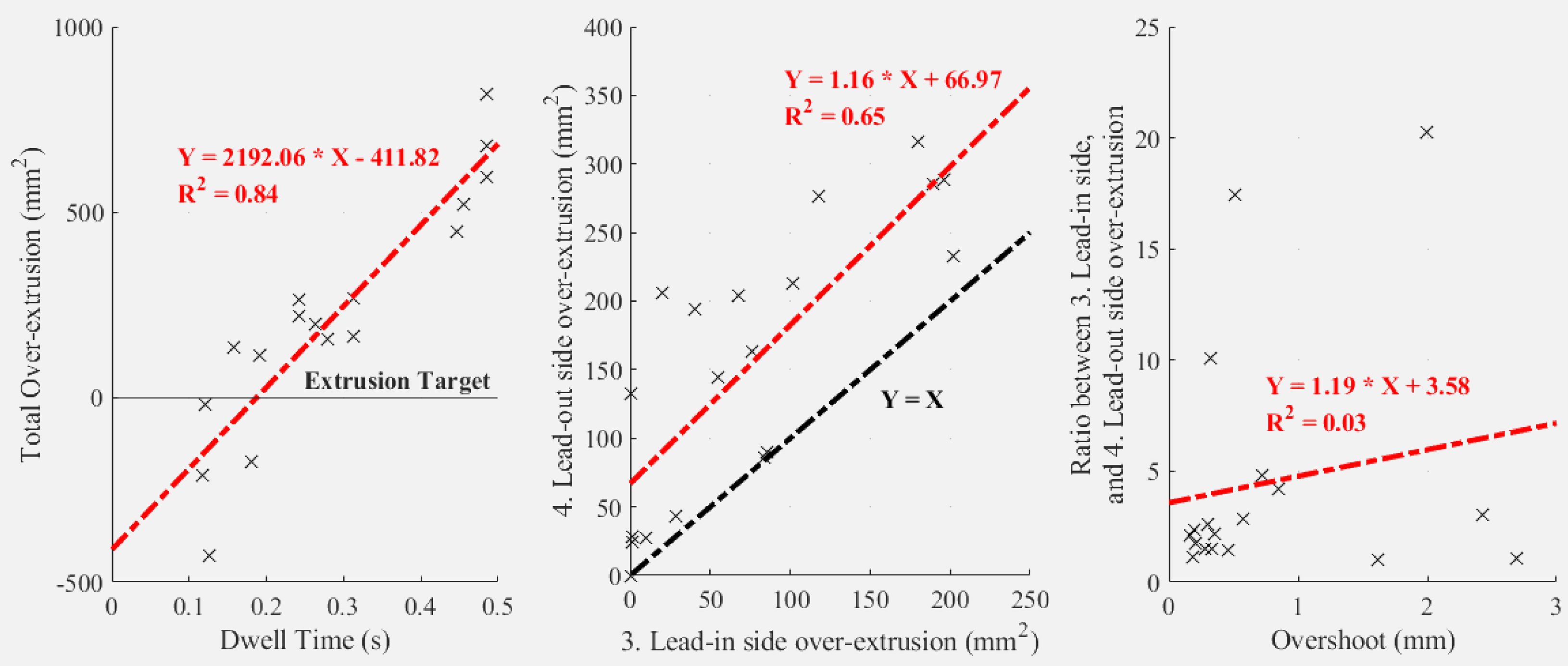
The profile of each corner of the 8 samples is imaged using a machine vision camera, and analysed in NI Vision Builder. The over- and under-extrusion zones are highlighted using edge detection (shown right). This allows the correlation of motion settings with motion paths, and ultimately, with printed part geometry.



5. Results



Results indicate that control of several key parameters can cause a considerable reduction in motion error. In the swarmplot on the left, the Completion Time Error (%), of each measured sample is shown. The red samples are those which contain no cornering instruction, have high set acceleration limits, and have a non-'fine' 'zone' parameter (which is a robot-specific control parameter). When removing these samples, a reduction in the range of errors is seen from ~14% to ~2% (blue). Similar relationships are seen for dwell time in corner sections, and the overshooting distance.



Finally, the motion parameters are correlated with the regional over- and under-extrusion at corner sections. Firstly, the total amount of over-extrusion is found to be proportion to the additional dwell time in each corner. Secondly, The location of over-extrusion is found to be asymmetric with respect to the nozzle direction. ie., the amount of extruded material in the lead-in direction is shown to be larger than that in the lead-out direction for all printed corners. Finally, there is found to be no effective relationship between the overshoot characteristic, and the ratio between the lead-in, and lead-out over-extrusion. This indicates that mechanical overshooting is not a major contributing factor to the observed asymmetry in the corner sections. The appropriate control parameters are now used as part of the concrete printing process at Loughborough to decrease print errors on all prints.

References
[1] Grasser G, Pammer L, Koell H, Werner E, Bos FP. Complex architecture in printed concrete: the case of the Innsbruck University 350 th Anniversary Pavilion COHESION. InSecond RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 2 2020 (pp. 1116-1127). Springer International Publishing.
[2] https://www.incremental3d.eu/projects.html