Robotic 3D Printing for Complex Geometries

MEng Project Scoping & Planning Report

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Project Scope and Aims

Three-dimensional (3D) printing offers many advantages over traditional manufacturing techniques. It can allow for the generation of complex structures both internally and externally, which is not achievable with subtractive methods [1]. By utilising a 6 Degree of Freedom (DoF) robotic arm with a print head directly attached to the end effector, the orientation of the print head can be varied during the print to alter the direction of material deposition.

Scope

One of the main issues with Fused Deposition Modelling (FDM) 3D printing is the stacking of layers in the XY plane [2]. This limits the geometry achievable, and means the resulting component is weaker across the z axis [3] [4].

6 DoF robotic 3D printing addresses this issue by allowing for the deposition of material in any orientation. This broadly widens the manufacturing potential, allowing for 3D printing on non-planar surfaces [5] [6] , support minimisation [7] [8] and variation in layer deposition for control over structural properties [9]. The attributed large build volume associated with the use of a robotic arm also allows for wider application of 3D printing, such as in the construction industry [10].

This project starts at the system integration stage; as such it would be infeasible to demonstrate non-planar printing within the 12-week time frame. Instead, the goal is to create a fully independent 6 DoF 3D printing system that is able to replicate the process used in FDM 3D printing.

Aims

The purpose of this project is to demonstrate the capability of a 6 DoF 3D printing system. This will involve establishing a system capable of converting an input file into a full print path, with an integrated bed levelling solution [11]. This will allow for future developments of the system to improve its capabilities, including printing on different surface topologies and in different orientations,

Figure 1 outlines the main intentions and deliverables for the project, labelled with references for following sections.

REF	AIM	SUB REF	DESCRIPTION
1	System holds all equipment for 3D printing	**1.A**	All components are mounted to the machine. Cables running to components. Print bed set up in front of machine.
		1.B	System retains full range of motion.
		1.C	Bed height and level fully adjustable.
2	Extruder capable of extruding filament on demand	**2.A**	Extruder is capable of reaching and maintaining an acceptable temperature
		2.B	Extruder can extrude a demanded length of filament
3	Printer capable of completing a series of test prints	**3.A**	Printer is able to match print and extrusion speed
		3.B	Printer can complete a series of test prints to demonstrate capability
4	System capable of performing autonomous bed levelling	**4.A**	Printer can take a single bed height measurement
		4.B	Several measurements used to autonomously correct for bed level

Figure 1 - Table of aims.

Project Objectives

To gauge the effectiveness of the system, a specific set of objectives have been laid out. These have been quantified to provide measurable metrics of the systems performance.

Build

The objective for the system build have been outlined in Figure 2. The rotation tolerance of ±180° at the wrist will still allow for full range of motion of the arm without the risk of damaging cables [12]. The design envelope has been specified in the arms user manual [13], and the bed adjustment tolerance is based off that of a conventional 3D printer [14].

REF	OBJECTIVE	TOLERANCE
1.A	• All components fit and mounted within design envelope in manual • Robot arm doesn't come into contact with components	±1mm
1.B	• Cable routing allows sufficient joint rotation • Arm maintains full range of motion	Joints maintain rotation of ±180°
1.C	• Bed height adjustable • Four corners individually adjustable to perform level	Corner height adjusted ±5mm

Figure 2 - Objectives for build.

Extrusion

The objectives for extrusion control have been outlined in Figure 3. The temperature range has been based off the typical operating range for a conventional 3D printer [15] [16], and the extrusion range is based on allowable tolerances from e-step calibration [17] [18].

REF	OBJECTIVE	TOLERANCE
2.A	• Extruder to maintain a suitable temperature range • Temperature range maintained whilst printing	±5°C over one hour standby, or 1 minute extruding
2.B	• Extruder extrudes the requested length of filament on demand	±0.5mm

Figure 3 - Objectives for extrusion.

Print Testing

The objectives for print testing have been outlined in Figure 4. Effectively matching the travel and extrusion speed will result in a print line of constant width, which has been specified based on allowable tolerances in conventional 3D printing [19]. Acceptable dimensional tolerances have also been based off conventional 3D printing [20] [21].

REF	OBJECTIVE	TOLERANCE
3.A	• Printer matches travel and extrusion speed • Resulting print line of constant width	Line width 100% to 120% of the nozzles diameter
3.B	• Printer produces dimensionally accurate prints • Prints accurate in x, y and z axes	±0.5mm

Figure 4 - Objectives for print testing.

Bed Levelling

The objectives for bed levelling have been outlined in Figure 5. The tolerance for single point measurement has been based on the tolerance in z height measurement of similar robotic arms [22], and the reasonable variance is based off the typical variance seen in conventional 3D printer beds [23].

REF	OBJECTIVE	TOLERANCE
4.A	• Can take single point bed measurement • Calibrated for distance between nozzle and bed	±0.06mm
4.B	• Printer can account for reasonable variance in a print bed	±0.1mm, maintaining line width specified

Figure 5 – Objectives for bed levelling.

Project Plan

To make the project more manageable, it will be broken down into three phases, with each phase representing a key milestone in the development of the system. Phase 1 will focus on the mechanical aspects, phase 2 will begin printing and testing, and phase 3 will be focused on using the bed level sensor.

Phase 1

This will involve the integration of the extruder, bed level sensor, microprocessor and filament reel onto the arm. A print bed will also need to be set up in front of the machine. This phase is marked as complete once all components have been successfully integrated into the system, and the system meets the build objectives previously outlined. The aim is to complete this phase within the first 4 weeks of the project, as to not delay phases 2 and 3.

End Effector Integration

Both the extruder and bed level sensor need to be mounted as the tool to the end effector. Since these are common hobbyist components, models of these have already been generated [24] [25] , as such the required mount can effectively be modelled and designed. This can then be manufactured in house.

Since several power and signal connectors will run to these components, cable runs will need to be established and mounted to the machine with sufficient strain relief, without inhibiting its range of motion.

Microprocessor Mounting

A mounting plate is required to attach the microprocessor to the arm. The chosen mounting point will be halfway up this arm, indicated as zone A on Figure 6, reducing the total length of cable required as much as possible.

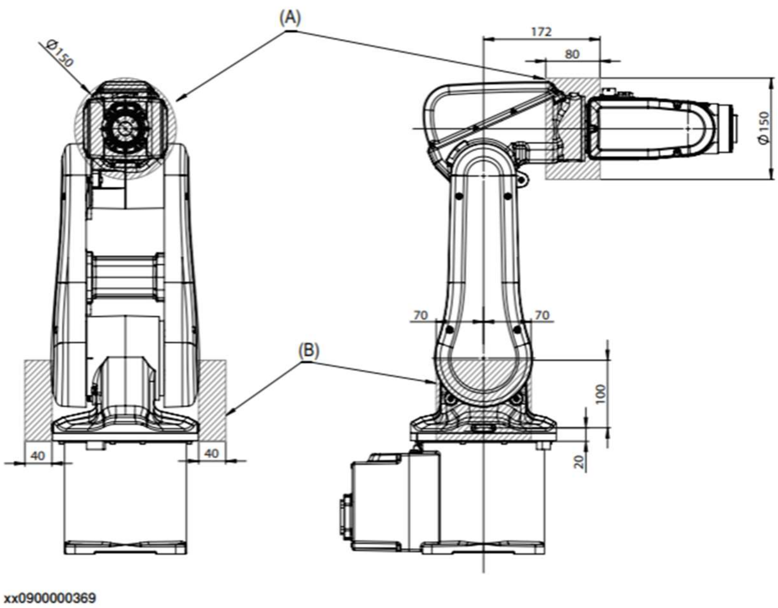

Figure 6 - Diagram indicating safe mounting zones on robot arm [13].

The mounting plate will be modelled and produced in a similar way to the end effector mount. Care must also be taken to ensure components fit within the design envelope, such that they are not damaged during the arms movement.

Filament Reel Holder

This will be located on the lowest mounting points, indicated as zone B on Figure 6. The mount will also have to feed the filament into a Bowden tube, which will allow filament to be transferred from the reel to the extruder without becoming damaged or tangled. This component will again be designed and produced in a similar way to the end effector mount.

Print Bed

Components for this will be purchased to avoid the need for additional design time and manufacture cost. The system will use the same type of print bed as a conventional 3D printer, with bed levelling springs at the four corners. This allows for the levelling of the bed as true as possible before testing, as well as providing a degree of compliance, in case the arm is run into the bed. The conventional bed assembly will be mounted to the table in front of the arm.

Phase 2

The goal of phase 2 is to perform basic 3D printing with the established system. To do this the microprocessor needs to be programmed to control the extruder, and the robot's path needs to be plotted for test prints. This phase of the project will be marked as complete once these two aspects can be combined to print a 2D line, square and circle, and the performance of the system meets the Extrusion and Print testing objectives. The allocated time for this phase is 5 weeks after the completion of phase 1, to give adequate time for testing, tuning, and collecting data. However, controlling the extruder is not dependant on the completion of phase 1, and development can begin earlier if necessary.

Temperature Control

Since conventional 3D printing using Arduinos is already established, temperature control can be achieved by modifying existing sketches [26] . This script utilises PID control to prevent fluctuations in the print head temperature. The extruder will need to be tested to target temperatures in the 190-250°C range to ensure the PID tune can maintain temperature within the specified tolerance.

Extrusion Control

Extrusion is controlled by the rotation of the feed stepper motor. It is necessary to know how many motor steps relate to the length of filament extruded. The length can be fine-tuned through a process known as e-step tuning [17]. An initial estimate can be calculated using the extruder gear diameter and the number of steps per rotation.

Pathing

To control the robot, ABB has a software package called RobotStudio [27], which allows the generation and simulation of paths using Rapid code. By knowing the position of the table relative to the arms base frame, a path can be created, which will sweep the arm through the desired test shapes. This code can then be uploaded directly to the arm [28].

Phase 3

The goal of phase 3 is to implement a bed levelling method to account for any variance in the flatness of the print bed. This task will be broken down into three stages; taking a single point measurement, taking sixteen measurements over the print bed and using the measurements to calibrate the machine. Since this task is not reliant on extrusion, it is not reliant on the completion of phase 2, or the full completion of phase 1. This means work for this phase can be performed concurrently with other phases, however the focus should still be on completing phases 1 and 2, since they are necessary for the core functionality of the machine. The goal is to complete phase 3 within a 4-week period, to allow additional time for data collection and report writing.

Single Point Measurement

The BLTouch outputs a signal when within a certain distance of the print surface [29]. Therefore, to calibrate the reading, the z height of the arm should be slowly lowered with the sensor active, until the signal line changes. The exact distance between the nozzle and the bed should be measured, and the process should be repeated to ensure the measurement is accurate. With the distance between the nozzle and bed known, the z height of the arm can then be used to calculate the relative height of the bed at that point.

16 Point Measurement

A path can be generated which will sweep the arm through a 16-point grid across the bed. At each point the Arduino will need to log the z height. Once all the points have been collected, a mesh can be generated to analyse the topology of the bed.

Z Height calibration

Using the topology measurements, the path of a desired print can then be altered to account for any variance in the print bed. The effectiveness of this calibration can be tested by attempting measurements and printing on deliberately warped printing surfaces.

Timeline

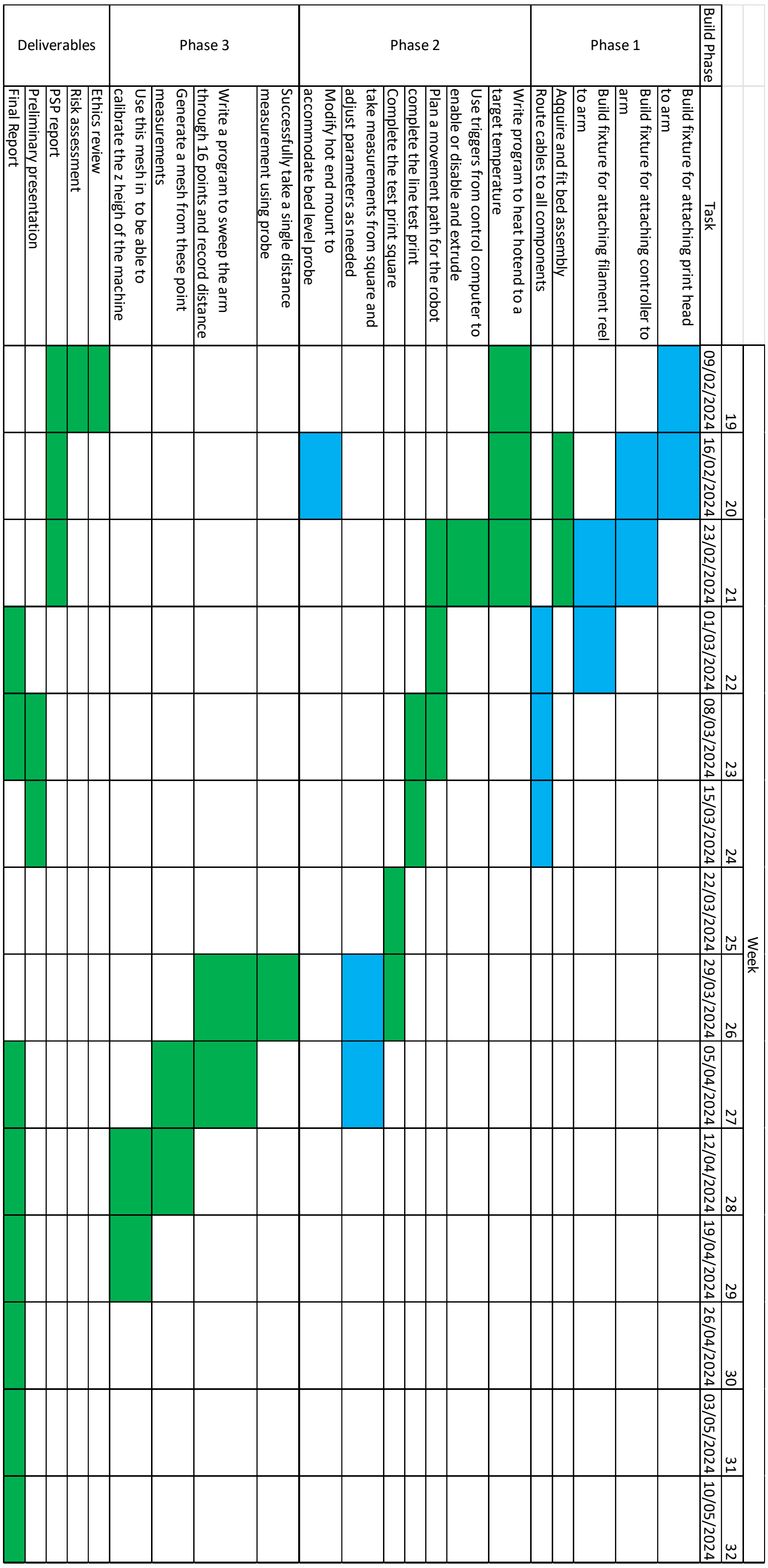

Figure 7 - GANTT chart outlining project timeline.

Figure 7 shows the GANTT chart for the project, in line with the describe project plan. Items that have been highlighted blue will be completed by other group members assigned to the project concurrently during phases 1 and 2, as to reduce the workload. These members will work on their own aspects of the project after phase 2, and so may have additional tasks which extend outside the scope of this chart.

Resource Planning & Cost Estimation

The project has already been allocated an ABB IRB 120 robotic arm [13], anE3D Hemera extruder [30], BLTouch bed level sensor [31], DM856 stepper driver [32] and an Arduino Uno [33].

The system requires a print bed assembly; this includes a mount, spring set and bed plate. Mounts will also need to be produced for fixing components to the arm, which can be manufactured in house.

Costs have been estimated using the 3D printing service quotes within the handbook [34]. Part weights have been estimated based off similar components listed on Printables [35] [36] [37]. For quantity, whilst only one of each component is required in the final design, two additional items have been accounted for in the cost analysis for critical components. This allows for the cost of a potential redesign or reprint in the event of component failure.

Additional Resources	Qty	Weight	Estimated cost
Print Bed Mount	1	N/A	£25.00
Print Bed Plate	1	N/A	£20.00
Bed Level Tooling	1	N/A	£14.00
Extruder Mount	3	25	£6.30
Dummy Extruder	3	50	£12.30
Microcontroller case	3	50	£12.30
Filament holder	1	75	£6.10
Bowden tubing	1	N/A	£10.00
Various Fittings	N/A	N/A	£10.00
		SUM	£116.00

Figure 8 – Cost analysis for additional parts to be purchased.

Figure 8 shows a cost analysis for the parts required. The total cost comes to £116, which results in an extra £385 allocated to the project. This provides significant headroom if any components need to be replaced, or any unforeseen components need to be purchased.

Risk Management

Figure 9 shows a completed risk analysis for the project and outlines how these are mitigated. Risk have been assigned a likelihood and a severity score, with the product of these indicating the overall risk to the project.

Risk	Impact	Mitigation	Likelihood (1-5)	Severity (1-5)	Total (1-25)
Components selected not being available	Unable to complete phase 1	• Identify alternative components that meet the demand • Order all known components at the start of the project	1	1	1
Delay / unable to manufacture components	Unable to install components on arm	• Submit designs asap • Use additional 3D printing resources (home desktop printers)	2	2	4
Designed mounts unacceptable / not fit for purpose	Unable to install components on arm	• Design parts with critical tolerance first to allow time for redesign	2	2	4
Existing components broken (Print head, bed level probe, Arduino)	Delays to phases 2 and 3, components need to be swapped out	• Test all components during phase 1 • Order new components as soon as old component damaged	2	3	6
Issues with robotic arm	Delays to ability to test print and level	• Transfer over to second arm	2	4	6
Communication Issues between arm, computer and Arduino	Unable to synchronise extrusion and movement process to print	• Test systems individually • Ensure all software up to date, components operating as they should	1	3	3
Cost higher than expected	Unable to purchase components required	• Double budget allocated • Significant headroom in costing analysis • Cost analysis account for redesigns	1	5	5
Time limit	Unable to finish project within 12 weeks	• Work beginning ASAP • Work parallelised where possible • Additional support from undergraduate students • Project open ended – final phase has no specific delivery requirements	3	2	6
Issues with control unit	Unable to control robotic arm	• Complete simulations virtually • Avoid tampering with control unit where not required	1	5	5

Figure 9 - Risk analysis table.

All risks identified score less than 9 total, meaning there's no significant impact to the running of the project. The majority of the risks relate to sourcing and manufacture of components. However, these scores are low and should not impact the project provided the mitigation methods are followed. The most significant risks relate to components breaking; care should be taken to avoid any failure of critical components, particularly the control unit and arm, since there cost to replace and down time are beyond the scope of the project.

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GenAI was not used in the preparation of this assignment.