**Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference**

Automated Assembly and 3D Printing for The Manufacture of Miniature Pipe Inspection Robots

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Abstract

Miniature robots consist of actuators, sensors and microprocessors combined into centimeter scale housing. In swarms they can have applications from infrastructure inspection to search and rescue. Traditionally, components are hand assembled and affixed using fasteners and wiring harnesses, applying design constraints, and limiting minimum size of potential devices. Through the hybridization of multi-material 3D printing and an array of ancillary tools including grippers, clamps and screw delivery systems, this work demonstrates the ability for one machine to print and assemble, miniature robots without operator intervention. The footprint of the platform is minimized, while maintaining a 250 x 200mm build area by using an intelligent tool changing mechanism that enables inactive tools to be stored when not in use. Complex assembly operations can be performed by integrating repositionable grippers and out of sequence manufacture. These capabilities were used to manufacture a miniature pipe inspection robot, with 0.2mm precision.

1. Introduction

Buried pipe networks are a key part of modern infrastructure delivering and removing materials such as water, gas and sewage from home, offices, and industrial facilities. Being buried however, introduces challenges to their maintenance and upkeep as monitoring their condition cannot be performed by basic visual inspection from the surface. In many instances problems with pipes are not found until long after the initial fault has occurred, and extensive damage has made the issue more obvious [1]. One series of solutions is the use of miniaturized pipe inspection robots that can be sent in swarms to autonomously observe, measure, and map the health of buried pipe networks [2, 3].

Traditionally, robots in this class have been hand assembled from a mixture of 3D printed parts, off the shelf components and fasteners such as nuts and bolts [4]. This approach, whilst simple to set up, is time consuming and labor intensive. For robots that typically work best when deployed in large groups, this introduces a major production bottleneck. Furthermore, the harsh environment that these robots operate in means that the likelihood of device loss or damage is high, so repeated production will be necessary.

The use of 3D printing has been highly beneficial as it automates some of the stages of manufacture, such as the chassis, wheels, or mounting brackets. The complex geometries enabled by 3D printing have also allowed the scale of these robots to be dramatically shrunk. Despite this, because the process is predominantly linear, with components being completely manufactured before assembly, design freedoms are limited as access for tools is required. By integrating assembly into the process, it is possible to realize out-of-sequence manufacture, whereby printing can be paused, some degree of automated assembly occurs, and the print resumes, removing the need for tooling access in the final parts. Automated assembly of 3D printed robots is a relatively new field with the author only being aware of one such example from Kosmal et al [5]. The group made use of a robot arm with a dual-purpose end effector with a fused filament fabrication (FFF) print head and an electromagnetic pick and place (PnP) tool to print some components, and then maneuver them into place. This approach enabled them to produce a functioning quadcopter without human interaction. It should be noted that the scale of the device was significantly larger than the limit of pipe inspection robots and used over-printing to fixate components.

Alternative works have explored the use of modular, self-assembly robots to allow small, discrete units form something larger [6, 7]. For pipe inspection this is potentially beneficial as it allows a robot significantly larger than the opening of pipe to enter, re-configure [8] and then survey. Additionally, if part or parts of the overall robot become damaged, a module could simply be swapped [9, 10] out improving the sustainability of the overall system. This does not however address the need to manufacture the modules themselves.

In this paper we demonstrate a factory-in-a-box style approach to hybrid printing and assembly whereby a single platform can print multiple material classes, manipulate, and assemble components in 3D space, and finally automatically dispense and install fasteners to enable future disassembly or servicing.

2. Machine Overview

To enable the automated manufacture and assembly of a small pipe inspection robot a bespoke hybrid manufacturing platform was developed. The machine used an orthogonal 3-Axis, core-XY motion platform, whereby the toolhead moves in X along a gantry that in turn can move in Y, whilst the bed translates vertically in the Z-direction. The core-XY layout kept the XY motors on the static portions of the machine, reducing the moving mass and in-turn providing two key benefits: greater acceleration for reduced cycle times, and greater payload capacity for more complex tooling. The bed was 250 x 200mm, heated, with a polyetherimide surface and mounted on a motorized 3-point leveling system.

The toolhead had an integrated locking and alignment mechanism based on an open-source design [11, 12] that meant the platform could change the active tool and allow it to perform different operations that would traditionally require unique, discrete machines. For producing the inspection robot, the platform was outfitted with two conventional fused filament fabrication tools, a rigid link parallel gripper with two rotational degrees of freedom, a vacuum suction cup, and an automated screw delivery and driver unit. The grippers and screwdriver are discussed in detail in the proceeding sections.

To ensure that the tools were precisely aligned, a bed mounted contact probe was used to calibrate tool offsets relative to the tool changing mechanism. This was coupled with a second contact probe on the toolhead itself that was used to probe the surface of the bed. The output from this was used to inform the levelling mechanism to tram the bed parallel to the gantry and to map minor deviations in the bed surface profile to maintain consistent 3D printing layer heights.

Software control of the multitude of electronic systems was achieved using the Klipper [13] 3D printer firmware. The full machine can be seen in Figure 1.

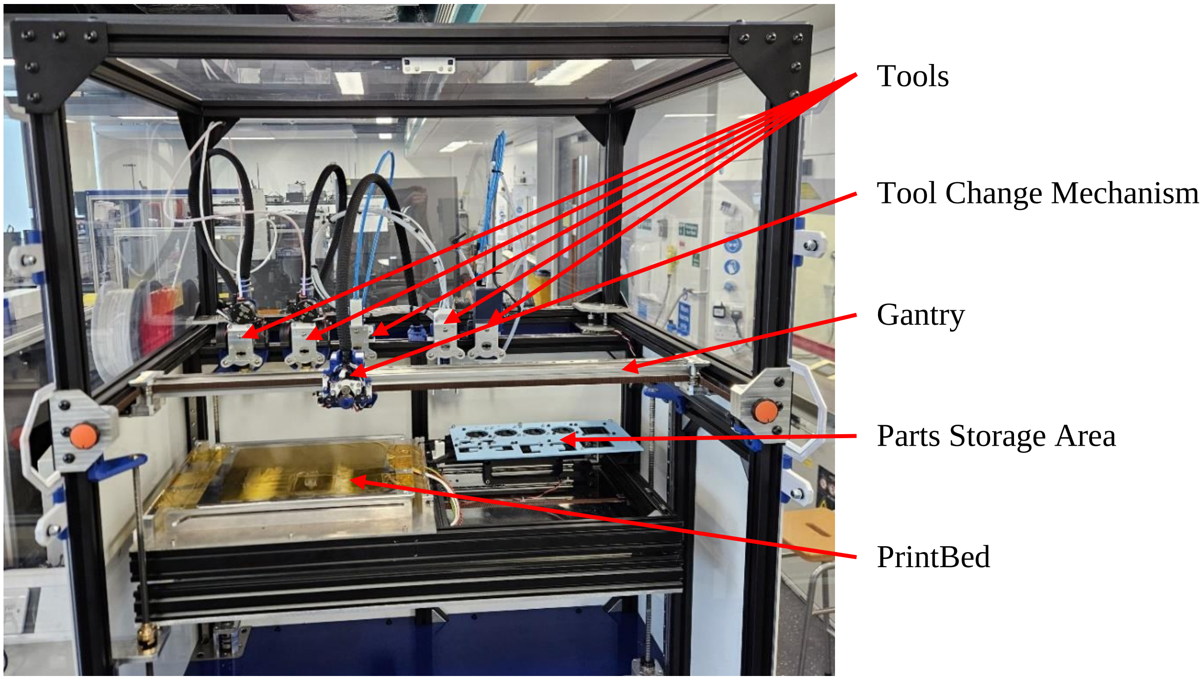

Figure 1: Overview of the autonomous robot manufacturing platform.

2.1 Grippers

When assembling devices, it is often a requirement to rotate objects relative to each other to align features, for example fitting wheels of a robot onto the shafts. Additionally, the orientation that parts are printed in may not be ideal for their assembly. As such, a key priority of at least one gripper design was to introduce rotational degrees of freedom to manipulate parts and enable more complex assembly steps.

To achieve this a tendon driven system was developed that used differential pairs of 0.54mm stainless steel wire rope wrapped around capstan affixed to an encoded servo. The wire ropes were then passed down 0.6mm ID PTFE tubing to the gripper where they were connected to various joints to provide motion. For rotation of the gripper about Z, the loose ends of the wire rope were affixed to a pulley integrated into a vertical shaft. To allow the gripper to tilt off axis, the wires connected to a joint perpendicular to the shaft. At the end of the joints was a rigid link, parallel gripper that used wire tension to close the jaws, and an elastic return spring to re-open them when the tension was relaxed.

In addition to the rigid gripper, a vacuum pick and place tool was added with an 8mm diameter circular suction cup and 1.5 bellow convolutions. The bellows allowed the suction cup to conform to small irregularities in the surface of components, such as the layering of 3D printed parts, or curvature on motor housings. Vacuum pressure was produced using a commercially available vacuum generator, that required a 5 Bar air input controlled by a solenoid. This configuration allowed the vacuum pick and place tool to theoretically lift 250g vertically. This tool was not selected for rotational operations as the bellows in the suction cup did not restrict rotation of gripped components, meaning that their position in 3D space could not be guaranteed.

2.2 Auto-feed Screwdriver

Existing fastener assembly automation systems on the market, even compact options, were found to be too large and heavy for the use in the machine. Such units also require a dedicated feeding system, sequence controller, and process controller. An example available on the market is the Weber SEV-P10 pick & place screwdriver. Despite being designed as a small and lightweight unit, it still measures 391mm in length and weighs 3.5kg (in the case of the lightest variant) compared to the 254mm length and 0.6kg weight of the custom solution.

The solution developed for this machine (see Figure 2) was designed prioritizing compactness, especially in the Z axis of the machine to preserve vertical build volume unlike off-the-shelf options. Considering the scale of the pipe inspection robots, M2 size cap-head bolts were selected as the standard fastener size for use, allowing the screwdriving tool-head to be optimized for that diameter of screw, and required torque.

With the use of a remote screw loading cylinder, it was possible for the machine to drive a range of M2 screw lengths depending on the assembly with a just-in-time approach making the system more flexible in comparison to a pre-prepared tape fed mechanism. When a screw was required, the cylinder rotated to select the appropriate screw length and the air supply solenoid was opened to propel the screw into the driving chamber through the only unsealed outlet via a PTFE tube. A high torque NEMA 14 stepper motor was used to drive the screws, with a current limit set to control torque. The stepper motor actuated via a low-pressure pneumatic cylinder to provide adjustable downward pressure to engage the driver and introduce compliance into the mechanism. With this system the motion of the screwdriver was controlled by the position of the build plate, eliminating additional actuators and position or pressure sensing in the tool-head.

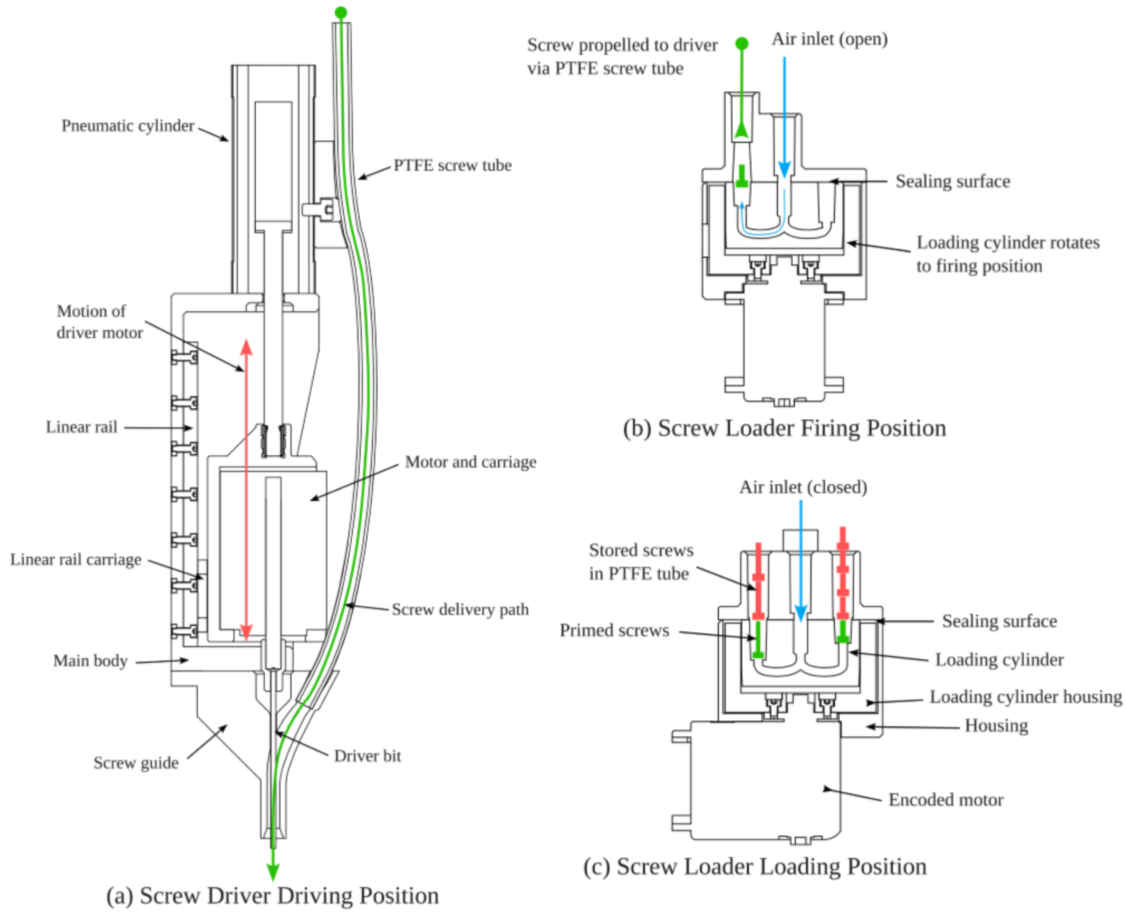

Figure 2: Cutaway diagrams of screwdriving system components illustrating a) the screwdriving tool-head in a lowered position, b) the screw loader in the firing position propelling a screw, c) the screw loader in the loading position with primed screws in the cylinder.

The flowchart in Figure 3 describes the screwdriving process operated via a macro with a screw size and position argument:

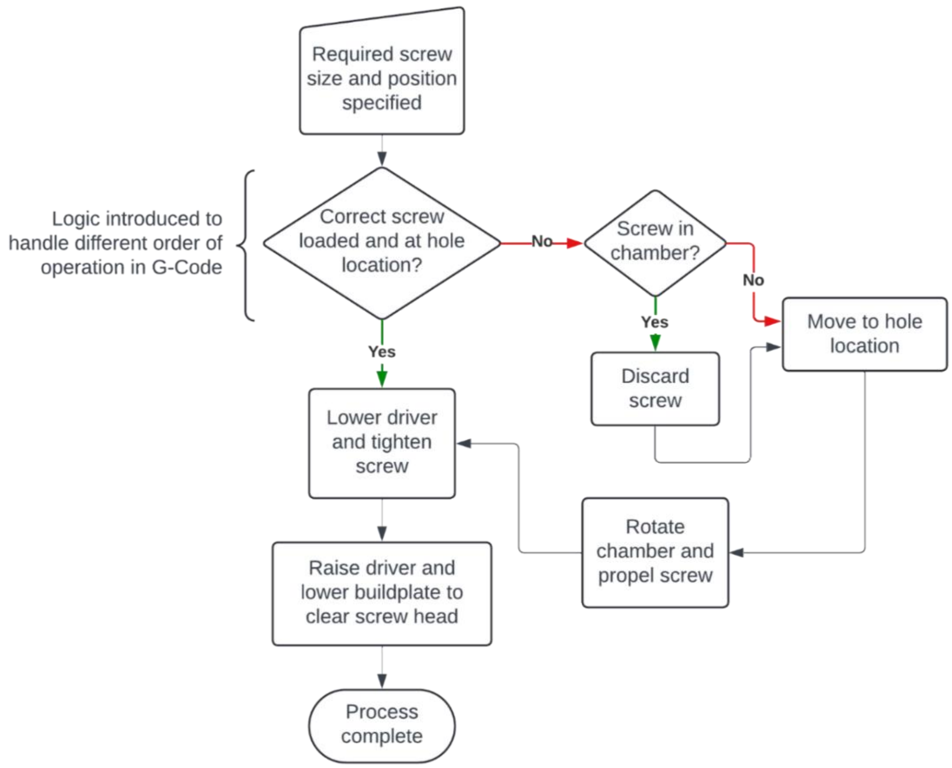

Figure 3: Flowchart describing process and logic for the fastening of a screw using the screwdriving tool-head and loader.

3. <u>Miniature Pipe Inspection Robot</u>

The miniature inspection robot (see Figure 4) consisted of four main sections; 1) monocoque chassis; 2) multi-material wheels; 3) custom PCB, sensors, and actuators; 4) wiring harnesses. When assembled, the robot can move in 2-axis and be controlled via a custom Bluetooth mobile application.

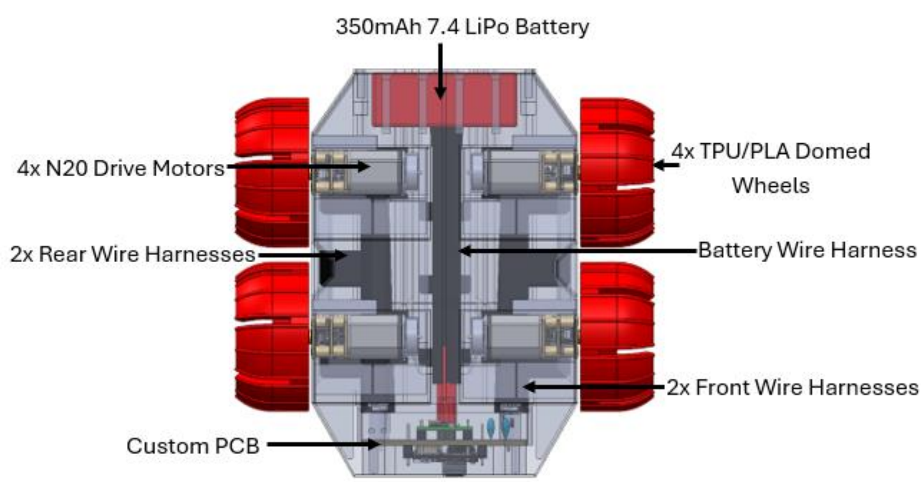

Figure 4: Final pipe inspection robot design.

3.1 Monocoque Chassis

Part strength and print time were the two main considerations when designing the chassis, meaning the robot can withstand harsh service conditions while also facilitating a high throughput of finished products. By matching the print parameters to the design, infill and as such print time was minimized. To print with no infill when using a 0.25 mm dimeter nozzle on the print head and printing with 2 walls, a 0.52 mm thick chassis was required. Similarly, 0.52 mm thick spines were added to the sides and base of the chassis, to increase strength and limit deflection on larger thin walls. Finally, to further reduce print time and increase the aesthetics of the robot, 45° overhangs were added where possible to remove material from the chassis. This had the added benefit of reducing the form factor, making the robot more suited to its application of pipe inspection. The final design of the monocoque chassis can be seen in Figure 5.

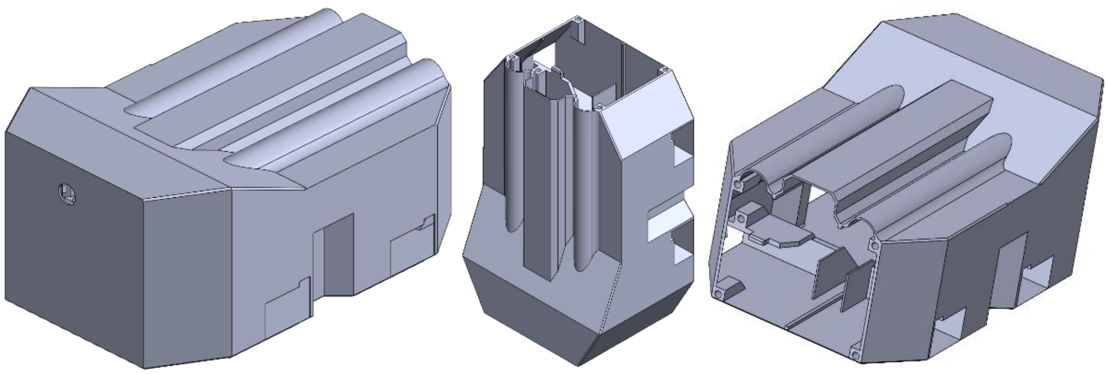

Figure 5: CAD image of the final chassis illustrating showing wall thickness, spines and 45° overhangs.

3.2 Multi-Material Wheels

Domed TPU wheels were designed to allow the robot to traverse and rotate within a pipe, maintaining continuous contact with the floor and walls, an advantage over traditional wheels. The lower durometer of TPU would have made single-material wheels ineffective at engaging with the motor's D-shaft leading to wheel slippage. A multi-material design was introduced, with a rigid PLA inner core for interfacing with the motors and a TPU outer tire for improved grip. Interlocking geometry was used to bond the two materials securely, preventing separation. This can be seen in Figure 6.

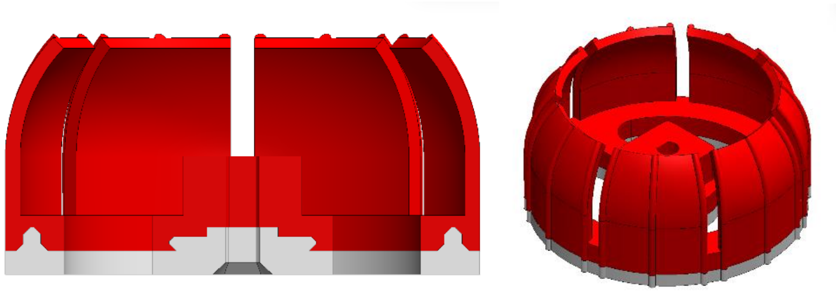

Figure 6: Cross-section of domed wheel with interlocking geometry between TPU (Red) and PLA (White) (Left) and final domed wheel aesign (Right)

3.3 Custom PCB, Sensors, and Actuators

To reduce the number of electronic assembly steps, a single PCB was designed to house the Arduino Nicla Vision mainboard, a TB6612FNG dual motor driver, and four 2-pin JST-XH connectors for the N20 drive motors. The Nicla is a compact 22.86mm x 22.86mm board that includes BLE, Wi-Fi, a HD camera, a time-of-flight sensor, a 6-axis IMU, and microphone. The total size of the PCB assembly was 45 x 45 x 17.25 mm.

3.4 Wiring Harnesses

Due to the flexible nature of traditional stranded copper wiring, and the small size of the JST-XH wire-to-board connectors, mating the electronics together posed a significant challenge. The current tooling does not allow for simultaneous manipulation of the motor and connector, making it impossible to reliably position the connector without coupling it to the motor using a rigid wire harness.

The harnesses were press-fit onto the encoder PCB of the drive motors, seating perpendicular to the motor face. A slotted guide ensured X-Y alignment, while chamfered leading edges allowed for easy interfacing with the chassis and account for minor misalignments. Clip features held the JST-XH connector, allowing slight rotational motion during assembly to accommodate insertion force and prevent misalignment.

A similar design principle was applied to the battery wiring harness, using three sets of aligning guides on the left and right of the chassis. This approach provided a more rigid, repeatable connection, aided by the chamfered connector pins on the PCB. final design of the front motor, rear motor and battery harnesses is shown in Figure 7.

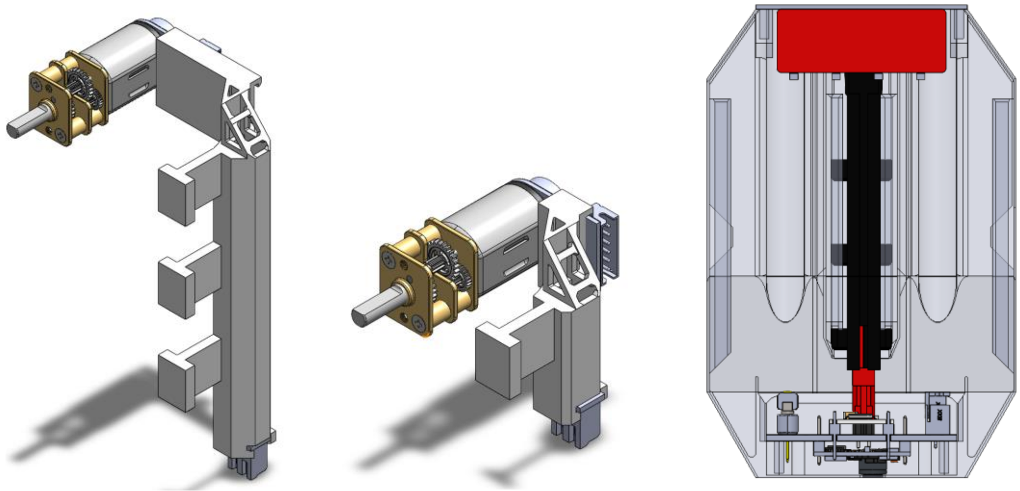

Figure 7: Rear wire harness (Left) and front wire harness (Middle) battery wiring harness (Right)

4. Automated Fabrication Procedure

While the design was informed by the need for strength and a low print time, the other main factor was the complexities involved with assembly throughout the print. Many iterations were needed as complications were discovered during the development process which are discussed throughout this section before the final G-code to print and assemble the robot is presented alongside the final product.

The first decision was to print the monocoque chassis upright, with the robot's face on build plate. This allowed components to be assembled sequentially, with each subsequent component interacting and building upon the last. The alternative option was to print the chassis with the base on the build plate, however this would prohibit the wheels from being located onto the motor shafts without further manipulation. The full flowchart for the print and assembly procedure can be seen in Figure 8.

Figure 8: Printing and assembly operations flowchart.

Careful consideration was needed to ensure that the print was stopped at a safe height before each stage of assembly. For example, during stage 1; the print was paused at layer 99, 2mm higher than the tallest component on the PCB. Pausing lower would have resulted in a collision between the nozzle and the PCB upon resumption of printing in step 2.

When designing interfacing components, a 60° chamfer was used to correct minor misalignments and improve assembly reliability. This design feature was used in the robot's wiring harness, motor bracket alignment pins, PCB housing, and screw bosses. The chamfer was particularly important during motor installation, as minor angular misalignment was amplified by the long lever arm of the wiring harnesses. This feature minimized the accuracy needed to interface the harness with the chassis, allowing the motors to be readily placed without binding.

To ensure reliable and repeatable assembly of individual components, a storage jig and baskets were designed and mounted to the side of the bed. This allowed non-printed components to be pre-loaded before a robot was built, and smaller parts, such as wheels and motor brackets, to be printed and stored for later assembly. Assigning a known location for each component enabled unmodified G-Code to be executed between build runs, allowing for continuous production. The baskets were oversized by 0.1mm and chamfers were added to the interfacing geometry to ensure accurate positioning while making component removal easy, reducing the chance of components being dropped during assembly.

Generation of the production file was semi-manual, with a standard multi-material capable slicer (Prusa Slicer, Prusa Research) being used to generate print toolpaths and pauses at the required heights. Tool change, pickup, manipulation, and drop commands were determined by manual, iterative tuning, before being placed at the correct stages of the file.

5. Results and Discussion

Once the production file had been tuned, the platform was able to autonomously build a functioning inspection robot from start to finish. The resulting robot was capable of locomoting inside a pipe and over small obstacles using Bluetooth control, while streaming live footage and sensor data over Wi-Fi. The use of part geometry to align components meant that the build precision was limited only by the fabrication accuracy, reducing reliance on gripper accuracy. Fabrication tolerances were measured to be consistently within 0.15mm of nominal on all alignment features. As a result, all components, including JST-XH connectors went together every time after optimization. The process took approximately 4 hours excluding wheel manufacture; these were-prefabricated by the platform and re-used for simplicity. Production is not entirely automated, with wiring requiring pre-made motor, wire, connector sub-assemblies specific to the robot being fabricated. The final robot after automated manufacture can be seen in Figure 9.

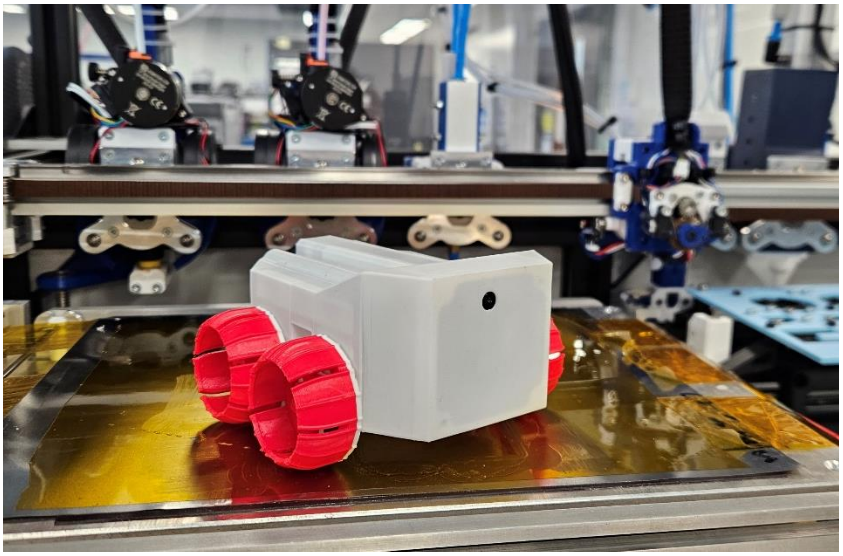

Figure 9: Final pipe inspection robot on the platforms print bed, after fully automated manufacture.

6. Conclusions

In conclusion, a factory in a box style approach to miniature robot manufacture has been developed. This approached used tooling for different capabilities in conjunction with a motion platform capable of selecting these tools and accurately positioning them. The platform was able to demonstrate multi-material printing, out of sequence manufacture, component manipulation and placement and screw delivery and driving. At this stage, software is a limitation, requiring manual design and optimization of the storage bay, and assembly toolpaths.

Acknowledgements

This work was funded by the Advanced Machinery and Productivity Institute, Strength in Places Fund from UKRI.

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