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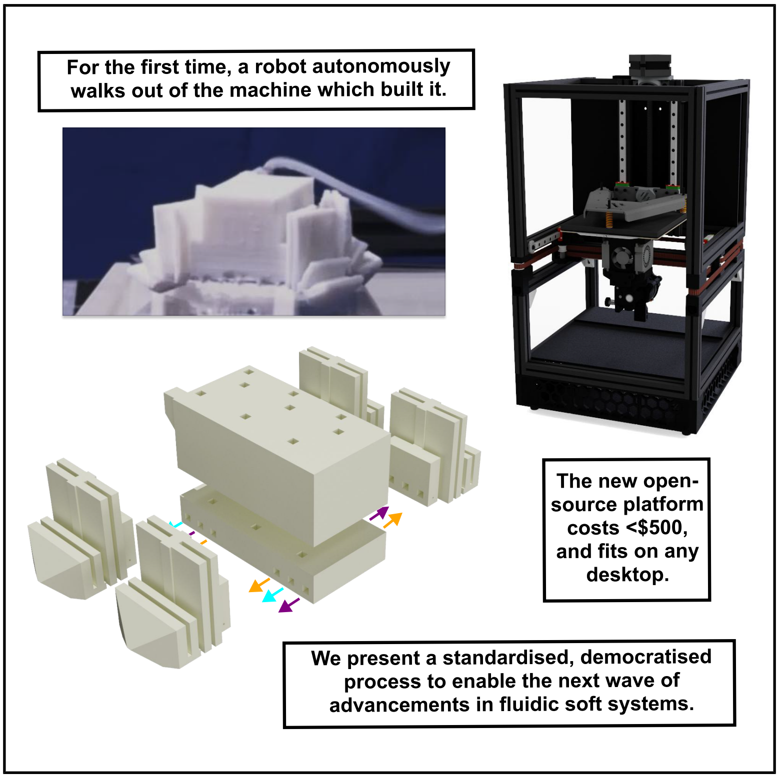
A standardized platform for translational advances in fluidic soft systems

Graphical abstract



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In brief

Soft robotics has huge potential but is limited by a lack of scalable fabrication methods. Our open-source flex printer enables rapid, reliable production of ultra-flexible soft robots with embedded fluidic logic, lowering barriers and accelerating innovation. We demonstrate this with a fully 3D-printed soft robot—requiring only one material and featuring embedded control—that can walk straight out of the printer, paving the way for widespread adoption and collaborative progress in the field.

Highlights

- Introduces flex printer: a low-cost, open-source platform for making soft robots
- Upside-down printing expands shapes and lets robots walk off the bed after printing
- Lays groundwork for standardized, scalable soft robot manufacturing
- Lowers entry barriers and invites collaboration to democratize soft robotics research

Extend & Scale
Work related to manufacturing, deployment, and technoeconomic/sociological considerations

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A standardized platform for translational advances in fluidic soft systems

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THE BIGGER PICTURE Soft robotics holds transformative potential for healthcare, manufacturing, and human-machine interactions, but progress in research and toward reaching commercial goals is limited by the lack of standardized, scalable fabrication methods. Our open-source flex printer platform addresses this gap, enabling rapid, reliable production of ultra-flexible soft robots with embedded fluidic logic. By lowering technical and financial barriers, this work aims to democratize access to soft robotics, accelerate innovation, and foster new applications that can benefit society in both the short and long term. Ultimately, this platform lays the groundwork for widespread adoption and collaborative advancement in the field. We demonstrate the capability of this technique by showcasing a fully 3D-printed soft robot, which has a bill of materials of 1 and embedded/embodied control and can walk out of the machine that made it.

SUMMARY

Soft machines are poised to deliver significant real-world impact, with soft robotics emerging as a key subdiscipline. These bioinspired systems leverage "softness" and are transforming human-machine interactions and delicate object handling, yet the field faces challenges in scalable manufacturing and standardized design. Here, we present the flex printer, an open-source, low-cost platform that reliably prints ultra-flexible soft robots with embedded fluidic logic using an innovative upside-down orientation, greatly expanding printable geometries. This approach enables robots to autonomously walk off the print bed immediately after fabrication, marking a significant advance in the field.Our results demonstrate a practical path toward standardization and scalable production of soft robots, both of which are essential for real-world impact. Through our open-source approach, we aim to lower technical and financial barriers. The flex printer platform broadens access to soft robotics research and application development, fostering community-driven innovation and accelerating progress in this rapidly evolving discipline.

INTRODUCTION

"Soft robotics" is a sub-discipline of a wider field of soft machines and soft systems.[1] Soft systems blend together advancements in three main areas: biological inspiration, materials science, and embodied/physical intelligence. Current cutting-edge research in soft systems is blurring the line between engineered systems and biology to create bio-robotic hybrids.[2,3]

Research activity in soft machines over the last 15 years has shown huge progress in fluidically controlled soft robots and has led to commercialized systems (cf. Soft Robotics, Bioliberty, Imago Rehab., Organic Robotics Company, and Fluidic Logic, among many others) that use "softness" as a key engineering feature to solve problems in interfacing machines with humans or delicate objects.

The path to translating lab advancements to real-world applications has undoubtedly been slowed by a lack of standardized manufacturing and design processes, such as those that have been developed for electronics and semi-conductor manufacturing. In this paper, we introduce a fabrication platform and set of design rules that we believe will lay the groundwork for enabling the facile translation of research developments between research labs and into scaled-up manufacturing.

Research into fluidic soft machines has brought innovations that promise to greatly enhance human-robot collaboration,[4] to enable systems with adaptability to unknown and hazardous environments,[5] and to create wearable, assistive devices.[6] This

Table 1. The path to helping soft robotics cross the translational barrier

	Stage 1: Early developments in desktop fabrication	Stage 2: Early developments in desktop fabrication	Stage 3: Standardized process for adoption at scale
Examples	Wehner et al.[7] Hubbard et al.[8] Buchner et al.[9]	Zhai et al.[10] Conrad et al.[11] Gepner et al.[12] Kendre et al.[13] Zhai et al.[14] Aygül et al.[15]	the flex printer platform proposed in this paper
Approximate printer costs	in excess of $100,000	$500–$3,000	<$500
Technology type	proprietary, cutting-edge printing methods	consumer-grade printers modified by individual labs or entirely custom-built	open-source platform co-developed by the community
Turnaround	slow (parts made to order)	rapid (in-house)	rapid (in-house)
Total print durations	depending on technology, post-processing requirements, and procurement times	hours to multiple days	hours
Level of required expertise	collaboration with industrial experts	specialized lab member know-how	democratized access for the entire research community
Goal	showcasing what is possible with the highest-precision techniques	validating that desktop fabrication is possible	making the manufacturing process a solved problem; shifting focus to delivering translational applications

emerging technology is completely revolutionizing our notion of the word "robot." The potential impact of the field is enormous. It does not merely refer to a differentiation in the shore hardness of the materials from which such machines are built; instead, it is used as an umbrella term for systems that are powerful demonstrations of embodied intelligence.

Standardization enables creativity and establishment of a marketplace

Dealing with matters related to materials choice and manufacturing methods is an inescapable reality associated with carrying out research work in this nascent, yet now maturing, field. Table 1 shows some of the timeline between basic research and translation to commercial activity. It is clear that the field is maturing toward a need for standardization to enable the sharing of digital designs that have been built for a standardized process—this route is what underpins the "FabLab" philosophy; the establishment of standards and foundry processes is what enabled the microelectronics revolution.

Designers in microelectronics can be "creative within the process," safe in the knowledge that whatever they design will be able to be manufactured. Intellectual property blocks, or "IP blocks," enable teams to inherit designs from libraries, and it enables a marketplace of licensing and sub-licensing.

The FabLab initiative enabled an open-source sharing of designs that can be manufactured on a set of standardized tools. Prototypes and products that are designed and built in any one FabLab can be reproduced in any other FabLab simply by sharing the digital files. Subscribers to the FabLab charter benefit from this standardized set of tools and processes.

Here, we want to release an initial piece of this prototyping/foundry process and also begin the groundwork for how the community can share these IP blocks—either open source or under a commercial license. This is described further in the section fostering collaborative development of the open-source platform.

The promise of robots that walk out of the machine

A substantial portion of the highest-impact work in fluidic soft robots from the past years has utilized 3D printing as the primary manufacturing method, largely due to its versatility and its ability to produce complex geometries. There have been many powerful demonstrations of what is possible when using the most cutting-edge, precise machines.[7–9,16] Unfortunately, it seems unlikely that technologies such as PolyJet printers or digital light processing (DLP) are solutions that will enable the field to scale sustainably; this is for three main reasons: (1) the current high cost of the printers, (2) their extensive physical footprint, and (3) their relatively low availability. The same factors apply to other technologies, such as stereolithography (SLA) and selective laser sintering (SLS) printing, which can also come with limitations in terms of printable geometries or require elaborate post-processing that is often carried out in dedicated environments due to the risk of contamination of hazardous solvents or powders.

Fused deposition modeling (FDM) has the upper edge in these three aspects, offering rapid in-house fabrication capabilities at an affordable price point. There have been several notable advancements in the space, and yet there are still major obstacles preventing truly scalable adoption. One of the main challenges is technical: fluidic soft robots require thin and highly elastic yet airtight membranes. Unfortunately, the lower the shore hardness of an elastomeric material, the harder it is to 3D print using FDM.

Filament extrusion systems involve pushing a thin column of thermoplastic polymer through a heated nozzle. This type of extrusion becomes highly problematic when the material is "ultra-flexible," which we define here as a term describing commercially available thermoplastic polyurethane (TPU) filaments with a

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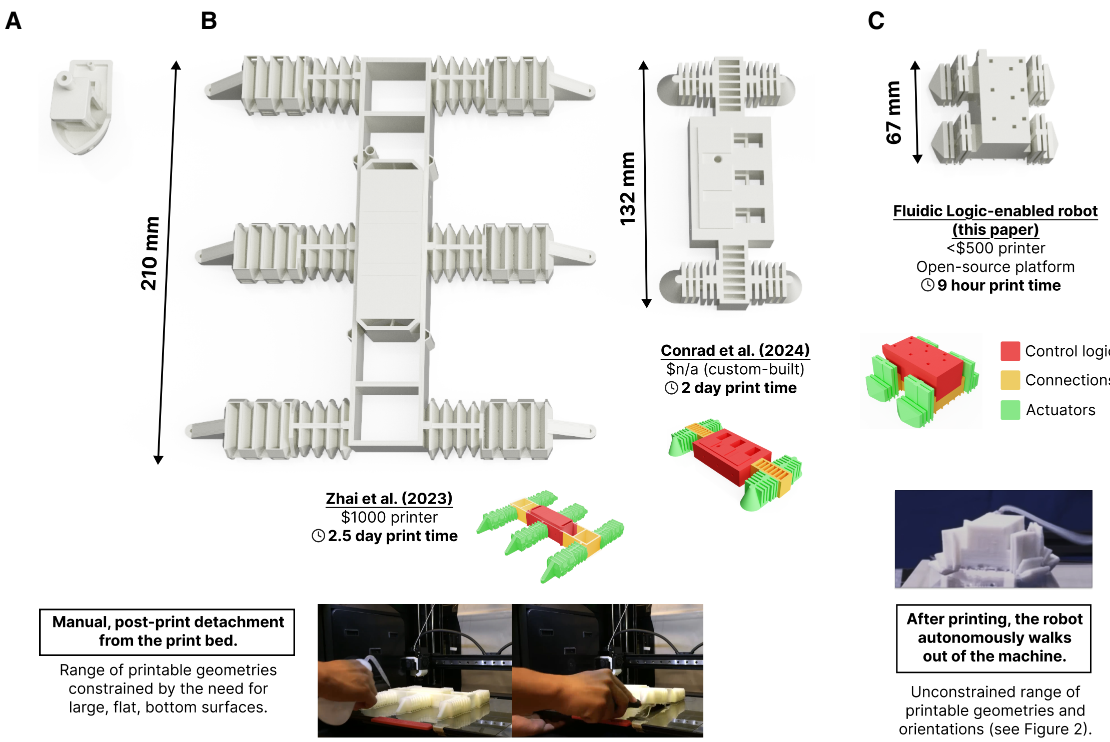

Figure 1. We propose a new benchmark for advancements in fluidic soft systems

(A) The "3D Benchy" test print has been commonly used to assess improvements in 3D printing speed, and quality.

(B) A monolithically printed, walking robot is a powerful demonstration of fluidic embodied intelligence and demonstrates the degree of integration of fluidic control systems. The key variables at play are the physical size of the robot and/or logic modules, total print duration, and any additional, in-built capabilities (a qualitative assessment of embodied intelligence).

(C) The robot we demonstrate in this paper achieves the first-time milestone of autonomously walking out of the machine that made it. Simultaneously, it exhibits a multi-fold increase in the level of system integration relative to its predecessors.

shore hardness of around 80 A and below. Extruding these materials is analogous to trying to push on a piece of string: it easily buckles and commonly results in extruder jams and inconsistent extrusion. The print defects that result from these issues are particularly problematic for fluidic systems that require near-perfect airtightness to operate reliably.[12,17] Despite a long history of promises of the idea of FDM printing soft actuators (e.g., the work by Yap et al.[18] in 2016), notable advancements in printing more advanced systems have only been more recent. Some, like Kendre et al.,[13,17] have made significant progress in printing elastic components for fluidic logic architectures, but the end systems still require additional rigid parts and manual post-processing assembly.

Being able to produce entire monolithic soft robots rapidly and reliably with integrated fluidic control, actuation, and sensing would not only enable new types of innovations in the research field but also unlock translational applications. The fact that these machines present no spark risk and are unperturbed by ionizing radiation or high-magnetic fields will enable innovation in high-explosion risk areas (oil and gas), nuclear decommissioning sectors, and space exploration, as well as biomedical devices that can operate inside an MRI machine. Such robots could be printed and deployed directly at the point of use in these environments.

There are two published examples of fluidic walking robots that have been printed monolithically[11,14] (shown in Figure 1B), but until now, no one has been able to achieve the "holy grail": printing a robot that autonomously walks out of the machine that made it. In this paper, we demonstrate how we managed to reach this important milestone. Moreover, we introduce a framework within which others will be able to easily build upon this result and make it much more than a one-off achievement. This robot has a bill of materials (BOM) comprising only one line—a flexible TPU filament. The implications of creating machines of this type are profound, as they have the following design for manufacturability characteristics: supply chain resilience, reduction in the number of failure points from sub-systems, and the potential to be decomposed and re-formed into new filaments, enabling a truly circular economy.

The flex printer is an open-source, low-cost platform that aims to facilitate the next wave of scientific advancements in soft robotics

In this paper, we introduce the flex printer, shown in Figure 2, an open-source design that can be assembled for less than $500 and solves the key reliability challenges associated with FDM printing ultra-flexible TPU, enabling virtually anyone to rapidly and reliably produce fluidic soft machines, even without prior

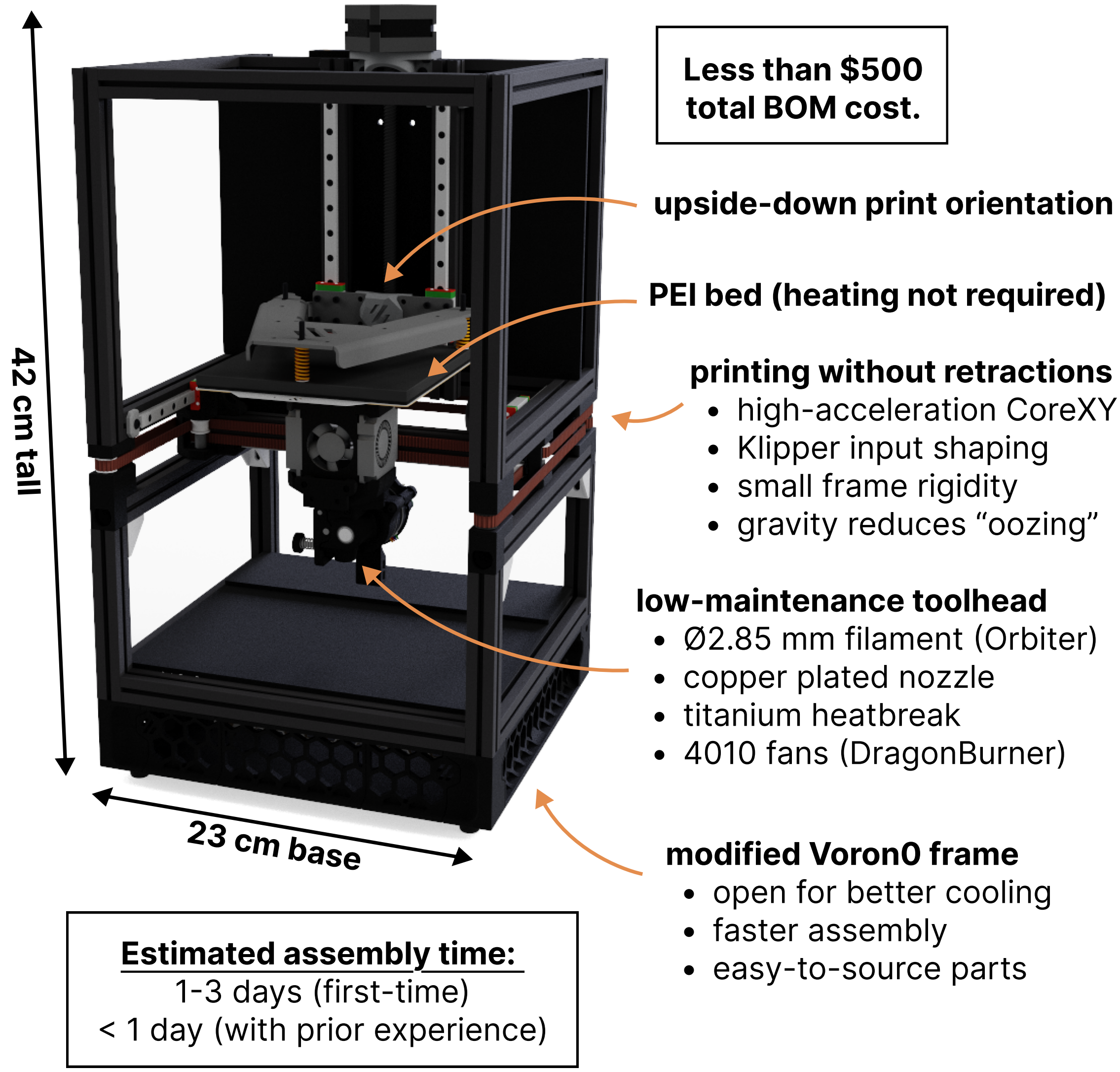

Figure 2. The key features of the flex printer

Its overarching design philosophy centers on removing unnecessary parts and introducing modifications that enormously reduce the need for regular maintenance. The printer is optimized to be as easy as possible to build and operate, even by newcomers to the field. For an in-depth explanation of the individual hardware features, refer to results and discussion where we also describe the possibilities granted through printing in the upside-down orientation.

experience. The flex printer can also create entirely new types of soft systems, thanks to a series of innovations described in results and discussion. We wish to make this a platform that will not only provide democratized, worldwide access to the technology but also help to standardize the manufacturing processes used in the field; we believe this step is necessary to truly enable soft robotics to scale.

RESULTS AND DISCUSSION

Here we describe five of the key hardware modifications that make up the flex printer. The sixth, and perhaps the most important, innovation is discussed in the section upside-down FDM printing enables rapid prototyping of previously unprintable, ultra-flexible structures, where we describe how printing ultra-flexible materials in the upside-down orientation enables one to print structures that were previously unfeasible.

Using wider filament diameters allows us to eliminate the fundamental issues of printing ultra-flexible materials

One of the biggest problems associated with printing flexible materials is that the column of ultra-flexible filament easily buckles under compressive load, i.e., when pushed through the heated nozzle. Trying to extrude too fast or with jerky movements results in inconsistent extrusion or even excess buildup in pressure, which can cause jamming of the filament in the extrusion system or even tangling around the extruder gear, requiring tedious disassembly to fix the fault.

We were able to overcome this issue by using a 2.85-mm-diameter filament (wider than the commonly used 1.75-mm variant). The larger cross-sectional area of the column makes it around 7 times harder to buckle (based on Euler's buckling theory, the critical buckling load P_{cr} for a circular cross-section solid column $P_{cr} \propto d^4$, so the ratio for the two diameters is $\frac{P_{cr1}}{P_{cr2}} = \left(\frac{2.85}{1.75}\right)^4 \approx 7.03$) and also means that the same extruder can push it through the nozzle with more force. This single change almost eliminated the jamming issues for us. Over 12 months of around-the-clock printing on 2 machines (using Recreus FilaFlex 63A,[19] which is the lowest-shore-hardness commercially available filament), we have experienced only three extruder jams; in neither instance did the filament wrap itself around the extruder gears. This modification significantly increases the tolerance to suboptimal print settings and toolpaths, decreasing the required level of expertise.

Printing at very high accelerations and travel speeds minimizes the need for retraction

After finishing one segment of a toolpath and moving on to another one, FDM printers commonly retract the filament slightly to prevent "oozing" over unwanted parts of the geometry. Printing without retraction can make it easier to achieve consistent extrusion, but it distorts the dimensional accuracy of prints. More importantly, it can cause blockages of fluidic channels, compromising the print reliability of soft robotic architectures. Zhai et al.[10] suggested modifying the geometry and slicing profiles to facilitate continuous "Eulerian" toolpaths that minimize the need for retraction. While we do not think this is strictly necessary (we successfully used retraction for all of our prints in Gepner et al.[12]), the use of retraction does require careful tuning, steepening the learning curve for new users.

The flex printer allows us to avoid any retraction tuning (without having to compromise on geometrical features) due to printing at very high accelerations (upwards of 10,000 mm^2/s) and travel speeds (upwards of 500 mm/s). When moving so fast between positions, the filament ooze is minimized, and retraction can be turned off completely. This capability is enabled by the CoreXY motion system, resonance compensation (Klipper "input-shaping"[20]), and the compact (42 $\times$ 23 $\times$ 23 cm), rigid frame of the Voron0 open-source design[21] on which the printer is based. The smaller 12 $\times$ 12 $\times$ 12 cm build volume is an adequate compromise, given the current focus on smaller-scale fluidic systems. A small print bed also minimizes the need for accurate bed leveling.

Excellent adhesion to PEI eliminates the need for a heated bed

The flex printer features a polyetherimide (PEI) sheet, which has excellent adhesion characteristics with TPU. The adhesion is so good, in fact, that the use of a heated bed is no longer required, even when printing upside down (the advantages of which we describe in a later section, upside-down FDM printing enables rapid prototyping of previously unprintable, ultra-flexible structures). Removing the heated bed significantly simplifies the assembly procedure and reduces the overall BOM cost.

Open design for better cooling

Better cooling not only allows faster and more reliable printing but also helps with bridging and overhangs, making complex geometries printable without supports. We use the DragonBurner extruder[22] with large 4010 fans to achieve better cooling. Our design does not use an enclosure; this open design not only improves air circulation but also simplifies the assembly process.

Extruder components that minimize the need for regular maintenance

Copper-plated nozzles have good thermal transfer characteristics, and TPU does not stick to them as easily as to typical brass nozzles. This quality minimizes the likelihood of filament jams and reduces the need for regular maintenance. The hot end features a titanium alloy heat break, which dissipates heat better than its stainless-steel counterpart. This characteristic prevents premature heating of the filament outside of the melt zone. We use the open-source, direct-drive Orbiter F2.85 extruder.[23] It is cheap and easy to source, yet its orbital gearbox generates ample amounts of force, making it easier to achieve consistent extrusion. The filament path is also reasonably constrained, minimizing the likelihood of the filament tangling itself into the extruder gears.

Upside-down FDM printing enables rapid prototyping of previously unprintable, ultra-flexible structures

FDM printing in the upside-down orientation has been a niche topic recently popularized by the open-source Positron project.[24] What had not been done before this paper is exploring this mode of printing in the context of ultra-flexible materials. We have discovered that printing upside down introduces revolutionary new capabilities for the development of fluidic soft systems, which we illustrate in Figure 3.

Wide, leak-tight bridging surfaces are now possible

Printing long, unsupported geometries is referred to as "bridging." When printing with regular filaments, optimal cooling and calibration usually allow the creation of high-quality bridges, i.e., without "sagging" with gravity. Ultra-flexible filaments are particularly challenging in this regard due to their elasticity; extreme sagging is the norm, and the drooping strands of filament do not fuse with each other, making it difficult to create leak-tight horizontal membranes for fluidic systems. Minimizing channel blockages is key to the successful printing of fluidic soft systems, so any sagging should be minimized, if not eliminated completely. Reducing this problem can be achieved with appropriate design for manufacture (i.e., minimizing unsupported horizontal structures), but such an approach constrains the range of printable geometries.

We discovered that when printing in the upside-down configuration, the issue is almost fully eliminated (as shown in Figure 3B). The flex printer is able to bridge significantly longer gaps thanks to this modification; this ability also contributes to greater consistency in printing channels for fluidic architectures.

There is a reduced need for supports

In the upside-down orientation, it is also significantly easier to print thin vertical membranes, as gravity now helps to stabilize

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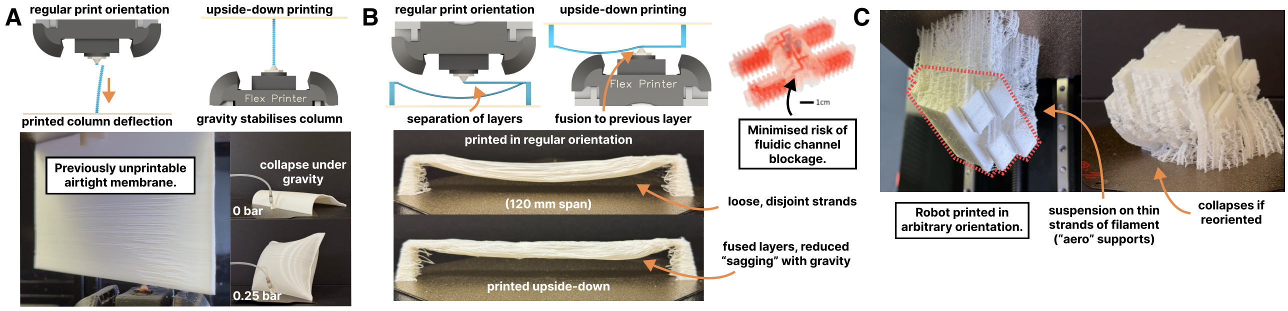

Figure 3. The flex printer makes it possible to create entirely new types of soft systems

(A) Printing in the upside-down orientation allows one to print thin, airtight membranes reliably even those of arbitrary heights (the pictured membrane is 118 mm tall, filling the entire printable volume). Airtight membranes are essential for the operation of fluidic systems.

(B) Avoiding blockages in fluidic channels significantly improves the reliability of monolithically printed fluidic architectures. Printing upside down also significantly improves the airtightness of horizontal, thin membranes.

(C) Thin column "aero" supports enable printing of virtually any geometry in any print orientation, as if "suspended in air." Similar types of structures could also be used to integrate new metamaterial geometries into soft systems.

the vertical structure (tensile load) rather than causing it to buckle (compressive load) under its own weight. This characteristic is of profound importance for printing soft systems and robots, which commonly require thin deforming membranes to operate. Figure 3A shows an example of a structure that would have been unprintable in the regular orientation.

Thin "aero supports" enable complex print geometries, which are "suspended in air"

Thanks to the tensile loading characteristics enabled by upside-down FDM printing, it is now also possible to print new types of support structures—an array of thin vertical columns (1–3 nozzle extrusion widths wide) that collectively support the weight of the printed object but are very easy to remove after printing—something that can be problematic with conventional TPU support structures (which can easily fuse with the object). We call these structures "aero supports" to highlight their light, minimalist footprint, which not only aids in their removal but also reduces the total print time and filament usage.

Another interesting characteristic of these supports is that they constrain the object almost exclusively in the axial (vertical) direction. In the section demonstrating a robot walking off of the 3D printer bed, we demonstrate how we utilized this characteristic to print the first robot to autonomously walk off the print bed right after printing. This feat had not been possible before, given that large, flat surfaces situated on the bed were required to make structures printable.

In Note S2 and Figure S2, we also discuss another new feature: the ability to leverage the engineered failure of aero supports to create thin-gap horizontal membranes that detach after initial pressurization. This capability enables the creation of new types of functional prints.

Demonstrating a robot walking off of the 3D printer bed

Fluidic robot design optimized for additive manufacture

Figure 4 illustrates the computer-aided design (CAD) render of the robot, along with its supporting structures. The gait of the robot utilizes the design by Conrad et al.,[11] featuring two "ligament" actuators to move each limb laterally and one "foot" actuator to lift the limb off the ground. To ensure that the robot would be capable of walking off of the bed, we needed to minimize its size and mass footprint. We were able to accomplish this by utilizing a highly integrated Fluidic Logic architecture; its geometry and routing are automatically generated and optimized for the 3D printing method. At the core of the robot is a CMOS pneumatic ring oscillator, which outputs a 3-phase oscillating pressure signal.

Test procedure

In order to operate the robot, we connected it (post-print) to a pneumatic pressure source providing a positive pressure of 2.25 bar. When making the connection, we took special care not to accidentally dislodge the printed supports, as that would constitute cheating in our aim of making the robot walk off the print bed. The robot had to remain hanging off of the build plate after connecting the pressure supply. The printed robot is upside down, so we designed a mechanism that automatically detached the build plate after the print was finished and reoriented the build plate plus robot into an upright position for the walking test. Figure 5 shows the key still frames from this entire procedure; see Video S1 for the full recording.

Fostering collaborative development of the open-source platform

How to become a contributor

We have decided to distribute ownership of the platform, hosting the printer files on "neutral ground": a GitHub repository[25] administrated through the Soft Robotics Forum, an online platform hosted by the IEEE Technical Committee for Soft Robotics; we hope that this will encourage others to contribute to the project as something that belongs to the whole community rather than one particular research group. We have also set up a dedicated channel on the Soft Robotics Forum server on Discord.[26] This online space is aimed at facilitating collaborative research between members of the international research community. The dedicated channel will enable newcomers to seek help and ask questions when assembling the printer and then later contribute to the project by offering their own advice, as well

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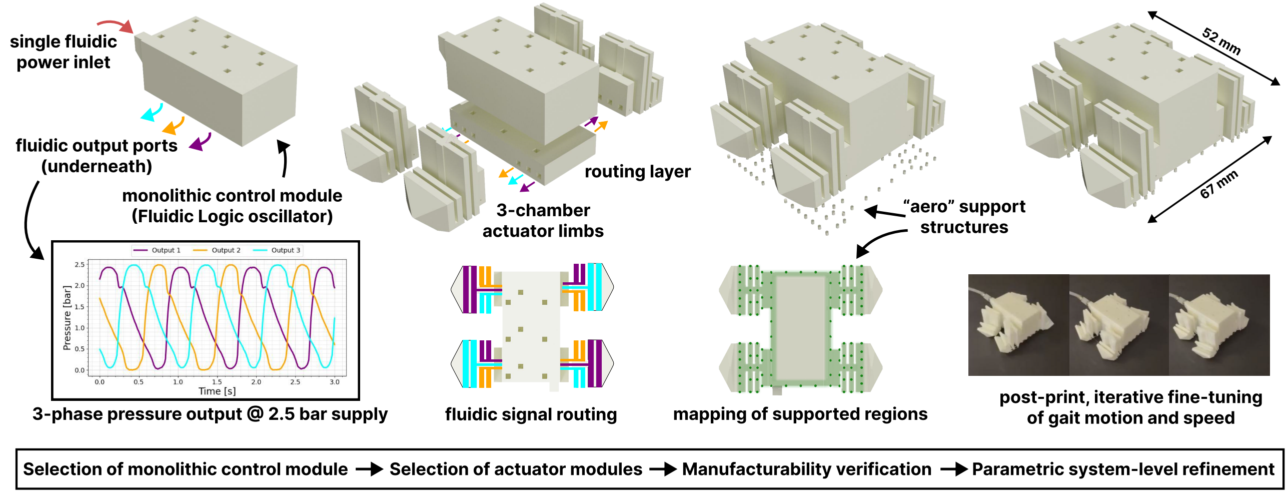

Figure 4. An integrated systems approach to creating robots with fluidic embodied intelligence
We build soft systems from libraries of standardized component building blocks, which come pre-optimized for manufacturability. The fluidic timing of oscillator components changes drastically after connecting any end effectors, connectors, or sensors, so refinement needs to be carried out at the system level. Due to the rapid prototyping speed of the flex platform, experimental characterization is a feasible option, even in the absence of a precise analytical or simulation model. This process is analogous to manufacturing processes utilized in the electronics industry, where, due to the complexity of the underlying physical phenomena, the refinement of models through experimental verification plays a crucial role.

as ideas and suggestions for improvements. All custom modifications can also be directly submitted as pull requests to the shared repository, which also includes detailed instructions for how to do so.

Directions for future development

We invite others to actively contribute to the project and help shape it into a platform that will offer democratized access to this technology to both researchers and students around the whole world. Some of our proposed suggestions for the next steps include implementing closed-loop printing and calibration methods such as those discussed by Wu et al.[27] and Read et al.,[28] multi-material printing capabilities such as these discussed by Aygül et al.,[15] and a re-design of the extruder to further improve cooling, shorten the filament path, and automate any occasional maintenance procedures (the full list of ideas is available on the GitHub page and will always remain open to new suggestions). Instead of competing to solve the same problems, we hope that the introduction of the flex printer platform will help make FDM printing of soft robots a solved problem and that it will empower the whole community to focus on making the next wave of breakthrough advancements in soft robotics.

The bestiary of fluidic machines, an online repository of reconfigurable fluidic building blocks

To help lay the foundation for the new economy emerging around the development of reusable fluidic system blocks (which we have discussed in the introduction), we have also set up another repository for sharing fluidic system IP blocks with the rest of the community.[29] This resource makes it easy to reconfigure existing fluidic component blocks into entirely new designs, for example, the designs introduced in this paper. We encourage others to submit their design blocks to the platform and help turn it into a thriving marketplace of ideas that will rapidly accelerate the pace of development of fluidic soft systems.

Conclusions

In this paper, we introduced the flex printer project, featuring an open-source FDM 3D printer that aims to solve the fundamental manufacturing difficulties that are holding back progress in printable soft robotics. We proposed a set of hardware modifications that allowed us to overcome fundamental issues related to the printing speed, reliability, and ease of use. We demonstrated how the printer allows us to reliably print ultra-flexible materials without requiring extensive, specialized knowledge. We also showcased how our new proposed method of upside-down printing with ultra-flexible filaments is ideally suited to printing fluidic control architectures and soft robots, which require thin vertical membranes and complex 3D geometries. To demonstrate the capabilities of this technology, we showcased how we used it to 3D print a soft robot that was able to autonomously walk off of the 3D printer bed right after it was printed, a first-time milestone in this field.

METHODS

Detailed methods can be found in the supplemental information and the extensive GitHub repositories that we reference throughout the results and discussion section.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Adam A. Stokes (adam.stokes@ed.ac.uk).

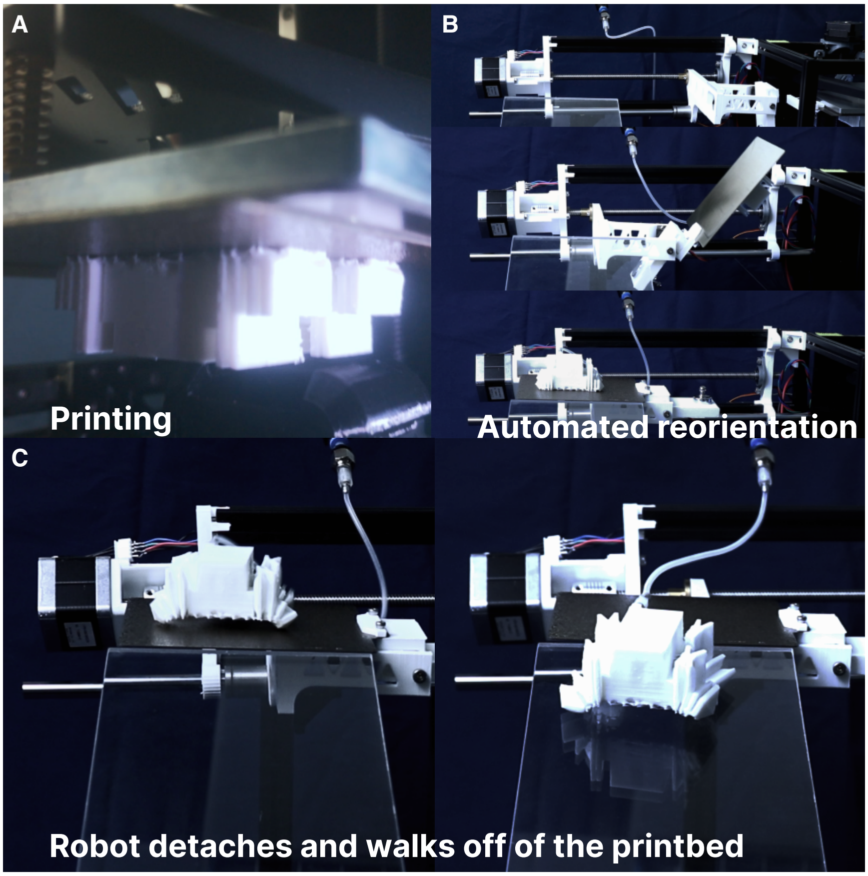

Figure 5. We demonstrate a robot that autonomously walks off of the print bed

(A) The monolithic robot is printed in an 8-h, 52-min-long single run.

(B) After printing, the fluidic power port is carefully connected, and the bed is removed and reoriented using an automated mechanism.

(C) The robot is powered by a supply pressure of 2.25 bar and walks off the print bed. See Video S1 for the entire procedure.

Materials availability

This study did not generate new unique reagents.

Data and code availability

All of the files related to the flex printer are available on the official GitHub repository (see the section fostering collaborative development of the open-source platform). The video of the walking robot is provided as Video S1. Uncut timelapse recordings of the print are available upon request. The CAD files of the Fluidic Logic oscillator are freely available on the Fluidic Machine Bestiary.[29] The supplemental information provides some more discussion of topics that were out of the scope of this study, including application-specific considerations such as printed part durability and strength (Note S1; Figure S1), characterization of the degree of airtightness (Note S3; Figure S3), practical considerations associated with upside-down printing (Note S5), and recommendations for the successful implementation of aero support structures (Notes S2 and S6).

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AUTHOR CONTRIBUTIONS

Conceptualization, M.G.; methodology, M.G. and J.M.; writing – original draft, M.G., J.M., and A.A.S.; writing – review & editing, A.A.S.; supervision, A.A.S.

DECLARATION OF INTERESTS

The authors are associated with Fluidic Logic Ltd., a stealth startup registered in Scotland (SC688151).

SUPPLEMENTAL INFORMATION

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DEVICE, Volume *3*

Supplemental information

A standardized platform for translational advances in fluidic soft systems

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Figure S1. The membranes of parts printed using the Flex platform exhibit high inter-layer adhesion*.* The pictured part is inflated to the point of translucency, but the individual layers remain intact, up to the point of burst failure.

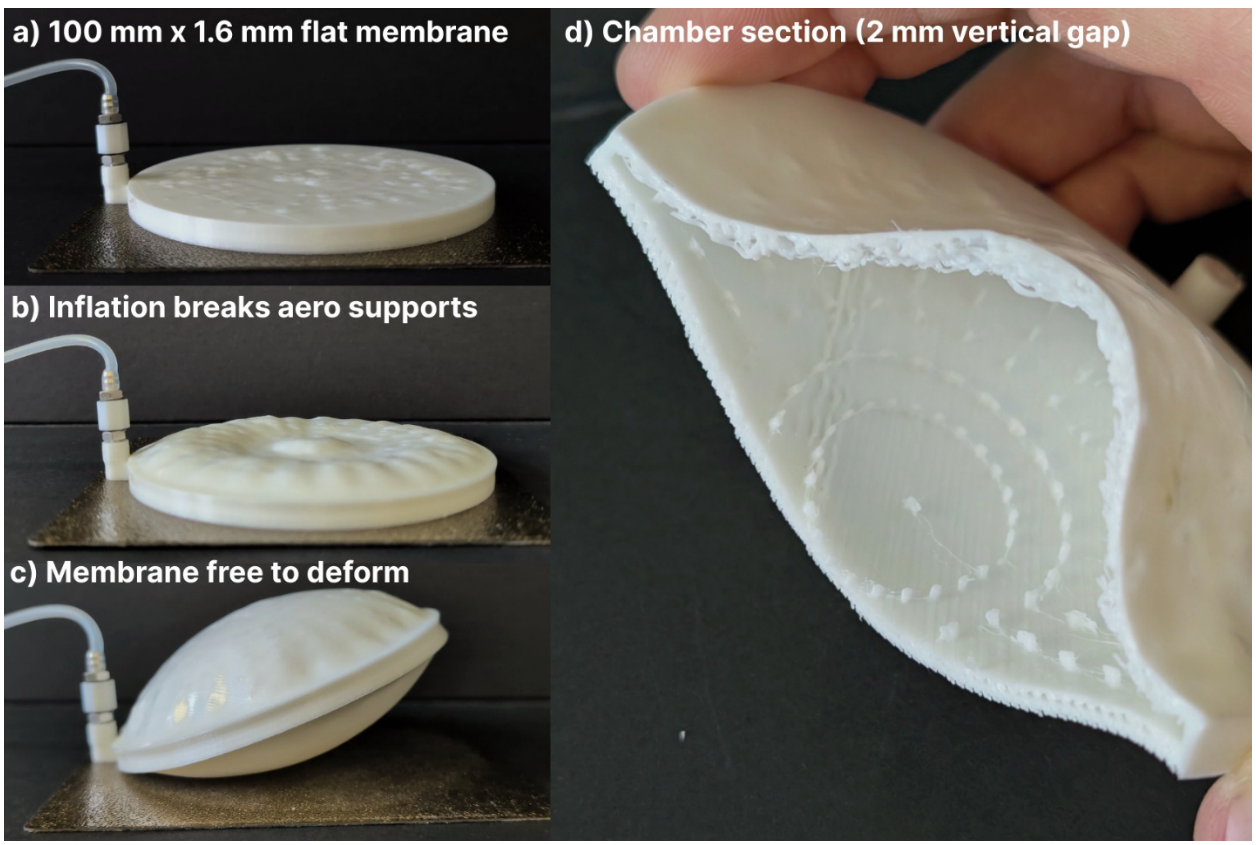

Figure S2. Aero supports enable to print large flat membranes without fusing to the previous layer. After pressurisation, the internal aero supports (visible in (D), which shows a section of the part) detach from the membrane, and allow for free deformation. This engineered failure mode allows to create new types of functional prints.

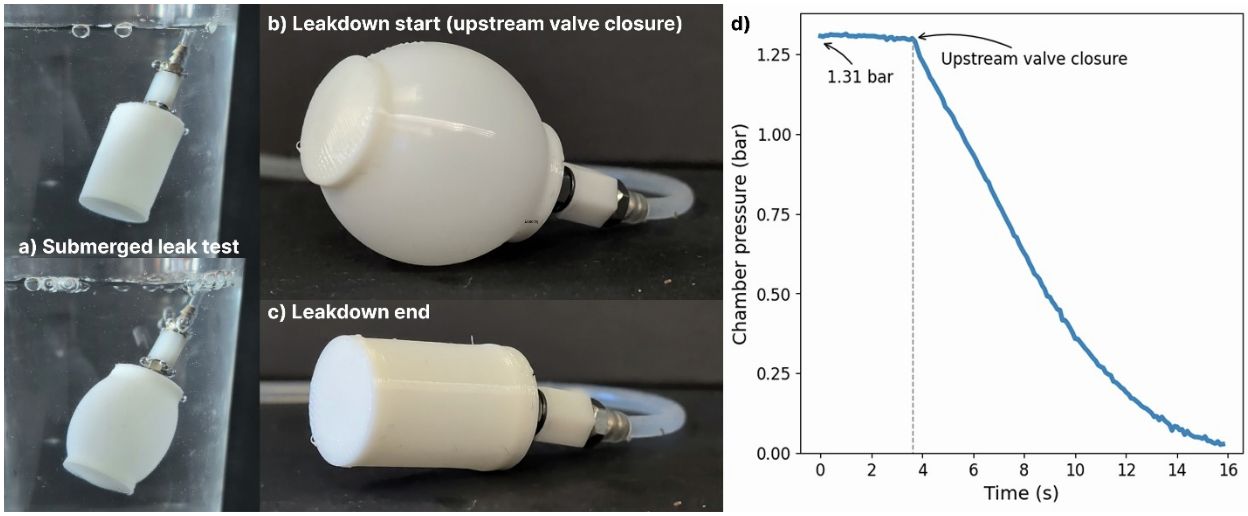

Figure S3. Examination of the airtightness of a sample part printed using the Flex Printer. (A) It is common for standard fluidic fittings to exhibit more leakage than the printed components. Panels (B) and (C) illustrate the leakdown of a thin-walled cylinder (its membrane is 0.8 mm thick, 20 mm tall, 15 mm in diameter). The pressure is set to the maximum before the onset of creep rupture. (D) Further optimisation of the fluidic fitting designs could extend the leakdown time beyond the observed ~12 second duration.

Note S1: Investigating application-specific performance metrics

The durability and strength of printed structures is an important practical consideration to consider in any project utilising fluidic soft systems made from ultra-flexible elastomeric materials. The exact performance criteria will depend on each individual use-case, as well as the thresholds for "good" and "bad" performance specific to that context.

In this paper, we have focused on the unique capabilities granted by the new printing method, as well as the ways in which the Flex platform offers the most unique advantages over other alternatives. For the prints which would not have been possible in the regular printing orientation, the fact that they operate successfully was the most important performance criterion in the context of this study.

There are potentially other interesting criteria which would be interesting to investigate, but were outwith the scope of this work. We hope that the Flex platform will help stimulate not only a plethora of new projects utilising fluidic soft systems, but also a series of investigations aimed at characterising the performance criteria specific to each type of application.

It is possible that printing in the upside-down orientation might lead to improvements in part durability, and strength. During printing, gravity acts in the direction of the nozzle rather than away from it; the generated backpressure helps to ensure inter-layer adhesion, in a similar way to the behaviour during bridging which we described on Figure 3B of the main text. The high degree of interlayer adhesion is shown in Figure S1.

At the time of writing this paper it is uncertain, however, whether any such gains will be significant enough to consider when compared to the effects of the extrinsic geometrical characteristics of each component. The same applies to any potential gains in part durability due to a smaller number of micro-cavities, made possible due to more consistent extrusion. Most likely the total operating lifetime of a part (e.g. the number of operating cycles) will be influenced much more by design decisions such as the chosen membrane wall thickness rather than small optimisations of the printing process, or the intrinsic characteristics of the printing material.

Note S2: Supporting large cavity structures using engineered-failure aero structures

Another feature of aero supports which is not explicitly explored in the main body of this paper is that they can be used to support large-area flat membranes, as shown in Figure S2. Such membranes can easily fuse to the layer below when printing in the regular orientation. The improved bridging when printing upside-down counteracts this effect, but aero supports also offer a complimentary ability: being able to engineer in membranes which separate only after initial pressurisation.

A single-layer (0.2 mm) offset between the aero supports and the membrane was sufficient in this case to ensure the supports peeled off with the action of the pressurised membrane. This demonstration is an example of how aero supports enable to print completely new types of not only geometrical, but also functional features.

Note S3: The effect of leaks on system performance

The system features a constant influx of air from the supply port, and as such the effect of any leaks on the timing of the Fluidic Logic oscillator is much more important to the performance of the robot than the total time-to-leakage under static conditions. The only instance where this would not be the case is if the leaks were so large that the actuators were not able to inflate at all, but in that instance the system would simply not function.

Figure S3 illustrates the outcome of a leakdown test on the cylindrical part. The figure shows how it is in fact the attached fluidic fittings that contribute to most of the leakage, rather than the structure itself. Whilst it is possible to engineer links with less leakage (in our experience adhesives like Araldite can be a simple solution, but irreversible connections of this type are impractical). Further optimisation of the connection mechanism was outwith the scope of this study, but it presents an area of interest and development for the future.

The caption for Figure 4 of the main text discusses how the timing of the Fluidic Logic oscillator is heavily affected by the RC loading of any externally connected components. The same applies to leaks, which introduce a parallel path to ground in the fluidic network, causing a reduction in the resistance of a given branch of the fluidic network; this reduces the RC time constant of that specific branch.

If the leak is at the location of the actuators, it will result in an increase of the oscillation frequency. If the frequency of oscillation is too high, there will not be enough time for the actuators to vent to atmosphere, and there would be no walking motion. The same can apply to internal leaks between different internal chambers of the device, which can also compromise the operation of the oscillator. We have observed how even minor leaks can result in significant differences in the oscillation frequency, which is why the high performance of the printing method is essential to guarantee correct device operation. The ability of the walking robot to function at all is the single most important metric in assessing its performance.

A detailed characterisation of the effects of leaks on system-wide timing is outwith the scope of this study, due to the large breadth of the topic. It is an ongoing topic of research in our group. Currently, our practical recommendation for system design is to minimise leaks as much as possible, and to rapidly iterate on versions of printed designs to examine the holistic system performance, i.e. after factoring in the effects of any print defects, leaks, etc.

Note S4: Selecting the right parameters for aero support structures

The density of the aero supports required for successful printing will completely depend on the printed geometry. To determine the right density, we recommend simple trial-and-error for each individual case, which is possible thanks to the short print times.

One thing we will note, however, is that there is a limit for how thin the aero columns can be, which is not related to their structural integrity. After a blob of material is deposited on each of these columns, the extrusion stops, and is only resumed after the extruder moves to the next column, creating a discontinuity in the extrusion profile. The effect on extrusion performance is somewhat akin to the pressure buildup with retractions, which we discuss in Section II B.

Too many starts and stops can result in inconsistent extrusions; this effect is mitigated through the high acceleration capabilities of the printer, which make the extrusion profile almost seamless, there are edge cases when the toolhead will fail to extrude a single blob of material on top of one of the aero columns. Since the column is only one blob wide, the next layers will have nothing to deposit new material on, and that column might not be printed successfully, especially if this underextrusion happens more than once.

Such aero support failures can occur both when the support density is too high (resulting in a long period of micro-discontinuities in the extrusion profile), as well as when it is too low (for example the toolhead has to move to the other end of the print bed just to deposit a single blob of material). The exact thresholds for failure and success will again depend on the specific example, so we recommend rapid iteration through trial and error to determine the right parameters.

Even high densities of aero supports tend to be easy to remove; they should just peel off by hand - like velcro. In our experience, instances of fusing to the printed structure are rare; if they do occur, it is always possible to add a single layer offset to ensure easy detachment (as we've done with the membrane in Figure S2.

We recommend experimenting with different diameters of the aero columns for your specific setup, though we have found that 1 mm tends to work well in most cases. This diameter ensures the slicing software generates a toolpath which allows for reliable material deposition with 0.4 mm diameter nozzles.

There is currently no easy way to generate aero supports in any freely available slicing software (Orca Slicer, Prusa Slicer, etc.). We have found it the simplest to just add them as part of the CAD modelling process, but it is of course also possible to use alternative software to achieve the same goal (Fusion 360 is one example - the "Additive" workbench allows to add supports of this type). We invite members of the community with experience in software engineering to help develop and add these types of features to the slicer software feature stack.

Note S5: Limitations of printing upside down

To date, we have only observed a few downsides of the upside-down printing method, primarily related to practical considerations connected to day-to-day operation of the machine.

Debris from the print area can fall into the extruder assembly. In our experience, this does not compromise the operation of the printer in any way, even over extended periods of multiple weeks without cleaning. Due to the action of the cooling fans, the debris is usually blown away. If it falls on top of the hotend cooling fan, or the surrounding areas, but these areas are not heated, eliminating any safety risks. It is, nevertheless, worth considering cleaning out these areas from time to time, as part of general maintenance.

It is more difficult to route the filament to the toolhead. When printing ultra-flexible materials, it is important to ensure minimum friction of the filament with any surrounding structures en route to the extruder, since this provides an additional obstacle to consistent extrusion. With regular-orientation printers, this is usually accomplished by removing any tubes intended to route the filament (even ones made from low-friction coefficient PTFE), and simply inserting the filament directly into the toolhead, usually from the top. Since in the Flex printer the toolhead entry point is facing downwards, it is not possible to place the filament spool there, unless the printer is lifted above the ground. Future versions of the printer might implement other ways to route the filament, but for now we have found it sufficient to place the filament spool holder beside the printer, and route the filament from that direction.

Previously uncharted modes of print failure. The ability to print completely new types structures also means that users will uncover new types of printing challenges. We have personally encountered two such examples:

- When the nozzle deposits new material, there is some degree of fusion to the previous layer; this generates a lateral force as the printhead moves in that direction. The action of this force can be made visible when printing extremely tall, slender structures. When pushed to the extreme, such "towers" become so easy to deflect that the printhead can drag the structure along with during movement. This effect can be mitigated by adjusting the Z-offset to reduce the inter-layer adhesion, but it is best to simply design structures with this in mind, for example by adjusting the wall thickness slightly to maintain at least the bare minimum level of lateral stability.
- Unsupported horizontal features will now droop in the direction of the printhead instead of the printbed. This means that, in extreme cases such unsupported cantilever beams, they can sometimes get in the way of the motion of the toolhead. It is, however, very easy to solve this problem by using using aero supports (such cantilever features effectively become suspended on the "aero" strings, just as the suspended robot demonstrated in the main text).

New challenges, and opportunities. In the main text, we demonstrated several structures which reach the limits of the print volume of this specific platform (120x120x120 mm). It will, of course, be interesting to see new versions of the platform in the future which will feature even larger volumes, so that it is possible to test just how big the printed structures can become, and what new challenges that might entail. We believe that the emergence of such challenges is something to look forward to, as it will hopefully correlate with exciting new developments of the technology. As mentioned in the main document, there are many possibilities for community-led projects on a variety of features, such as the implementation of multi-material printing, closed-loop parameter optimisation, as well as a plethora of new applications.

Note S6: Additional details on printing parameters, detailed printer schematics

As stated in the main text, the complete set of information about the printer is available on the publicly available Github repository (https://github.com/The-Soft-Robotics-Forum/flex-printer). The repository includes a link to the Onshape CAD assembly, which can be opened in a web browser for free to quickly look up and view the printer's components in greater detail. We have also provided a complete slicing profile with the default printing parameters used throughout the paper (220°C nozzle temperature, 20 mm/s speed, 0.2 mm layer height).