Formaflow: A Morphing Wearable That Lifts Hemlines for Mobility and Expression

Xochitl Ortega, Kamron Soltani, Prithvish Ganguly, Loris Emanuelli , *MECENG 292C – Design with Morphing Materials and Mechanisms, Fall 2025*

***Abstract*: Formaflow is a wearable morphing dress that actively reshapes its hemline to improve mobility while amplifying visual intent. Over a three-week sprint, the team built a doublelayer garment with integrated actuation that lifts the dress to prevent interference while walking, avoid tripping on stairs, and reduce ground contact in wet or dirty environments. Four servomotors pull tiled lifting segments and two servomotors drive octopus-inspired flippers, coordinated through wireless control. Tape-reinforced thread stoppers were devised to tune fold positions, increasing repeatability and clarity of the morphing silhouette. The resulting system demonstrates that dress morphing can serve functional and aesthetic goals simultaneously, offering a portable platform for future responsive apparel research.**

I. INTRODUCTION

Long dresses routinely compromise mobility on stairs, curbs, or wet ground. Existing solutions such as static hemlines or removable trains trade usability for style and rarely adapt on demand. Shape-changing garments and soft robotics show how material motion can communicate intent and provide utility [1], [2], [3]. Formaflow positions hemline morphing as both an assistive and expressive capability. The goal is to lift and sculpt fabric in context-specific ways: clearing steps, preventing tripping during walking, and keeping cloth away from puddles while preserving fashion value. We pursued three design objectives: (1) improve mobility for walking and stair climbing; (2) preserve comfort and wearability through concealed hardware; and (3) create an adaptive art that morphs. A custom mannequin was fabricated to enable fast iteration. The system was evaluated through on-body trials covering walking, stair ascended/descending and rain/dirt exposure, with emphasis on lift height, and comfort. Current and related explorations in responsive textiles and wearable robotics often prioritize sensing or haptics rather than expressive motion [4]. Our work instead designs motion as both communication and function. We draw from biomimetic soft arms for curling patterns [2] and programmable materials for staged appearance changes [3]. Our contributions are: (1) a double-layer morphing dress that blends functional lifting with expressive curling; (2) a taped-thread stopper strategy that turns low-cost threads into repeatable fold constraints; (3) a compact electronics and control stack with wireless presets and IMU-triggered auto-lift; and (4) an evaluation across mobility, cleanliness, and perception goals. The following sections unpack design decisions and report performance.

1

TABLE I: Functional requirements and achieved performance

Requirement	Target	Achieved
Toe clearance during walk	> 80 mm lift	120 mm lift, no ground contact
Stair auto-lift latency	< 1 step	Triggered within 1 step of pitch change
Rain/dirt protection	Hem above puddles	Hem raised above 20 mm obstacle
Visual intentionality	Smooth, staged motion	150–250 ms staggered actuation
Comfort and concealment	Hardware hidden	Double-layer corset, electronics bay

Table 1: Formaflow function requirements

II. BACKGROUND & REQUIREMENTS

The primary wearer scenario is a floor-length dress used in everyday and semi-formal contexts. Hazards include toe catching on the hem while walking, snagging on stair edges, and capillary wetting from puddles. These constraints drove a focus on slim mechanisms, concealed routing, and staged motion profiles.

Three user goals emerged from early interviews: (1) "I should be able to forget the system is there until I need it," (2) "Lift in a way that looks intentional, not like emergency avoidance," and (3) "Let me choose how dramatic the pose is." The first goal motivated the concealed corset and soft thread choice. The second led to staggered timing and the taped fold choreography and the third was addressed through manual mode with adjustable lift amplitudes.

From a morphing perspective, we sought to combine two behaviors: lifting (shortening) and curling (outward deflection). Lifting reduces ground contact, while curling enhances toe clearance and changes the shape of the dress. Alternating between them creates silhouettes that read as deliberate design gestures. The rest of the paper details how the requirements in Table I were translated into the implemented system.

We framed the functional goals explicitly around walking, stairs, and rain/dirt exposure. For walking, toe clearance needed to exceed 80 mm without adding weight at the hem. For stairs, actuation latency had to be below one step and avoid scuffing on risers. For rain/dirt, the hem had to stay clear of splashes while keeping the garment comfortable and breathable. These benchmarks informed thread routing, timing choices, and battery sizing

III. RELATED WORK

Responsive textiles and morphing garments have explored embedded pneumatics, shape-memory alloys, and responsive knits [1], [3]. These approaches emphasize material-driven deformation. Formaflow combines conventional fabrics with lightweight mechatronics to reach larger strokes. Wearable sensing literature highlights the value of low-profile electronics for comfort [4]. Our contribution is a hybrid garment that merges material driven movement with electronics to address mobility, cleanliness, and expressive motion simultaneously.

IV. DESIGN ALTERNATIVES CONSIDERED

We considered using shape memory alloys (SMA) due to their compact design and integration into fabric. We were inspired by past works with SMA wires with fabrics to develop cinching style patterns. However, due to budget and safety constraints, we opted to go with a cable and winch method instead. The SMAs must have ample amount of current going through the wire in order to contract, which dissipates heat and can burn the fabric and even the user. In addition, for the amount of current needed to actuate the SMAs the power supply would have to be quite bulky, making the dress too heavy and not wearable. We also considered alternative methods of actuating the fabric including a popsicle stick on a servo, continuous geared motors, as well as even heat changing properties.

V. METHOD

Development proceeded through parallel subsystem fabrication and iterative integration on a mannequin-based test rig. This section describes the hardware architecture, fabrication workflow, control implementation, and evaluation procedures.

A. *Mannequin*

A lifesize mannequin was made to make the design and development of the dress easier when prototyping. This allowed us to work on the wearable dress without a group member consistently wearing it; optimizing our time and workload. The designated group member wore a T-shirt and had duct tape taped around it to form the silhouette of the mannequin (can be seen in Appendix). This allowed us to work with the designated members' measurements and height. The taped shirt was removed with scissors and taped along the cut to make a hollowed figure. The cardboard was cut out to fit the holes and taped into place, leaving the neckhole open. We stuffed the mannequin with a piece of wood at the base, to make it more stable and easier to attach to the wooden support column. After, inside the hallowed body, we placed folded T-shirts where more support was needed, such as the base. We stuffed the rest of the mannequin with shredded newspaper to ensure it is easy to pierce with sewing pins and weigh overall as light as possible. Once the top of the body was complete we assembled a base out of wood and attached it together (Fig.1).

Fig 1: Handmade Mannequin made out of tape, t-shirt and wood.

B. Hardware Design

Six micro servomotors were selected to provide compact actuation with sufficient stall torque. Four servos drove pulley-routed lifting lines that gathered tiled textile segments along the hem, while two additional servos actuated biomimetic flippers, inspired by octopus-arm curling, to bias fabric outward and increase toe clearance. This distribution of actuators enabled independent or combined morphing behaviours, supporting mobility while maintaining garment coverage (Fig. 2).

Critical components were fabricated by fused filament fabrication, using PLA for structural elements and TPU for compliant interfaces. Stitching apertures were integrated directly into the CAD geometry to enable low-profile textile attachments without additional hardware (Fig 3.). Auxiliary components stabilised the corset and preserved alignment between the lifting spools and the garment, reducing frictional losses and limiting snagging during repeated cycles. Load paths were routed to keep reaction forces aligned with the corset (Fig. 4). The corset was designed to provide clearance for the motors between the bilayer fabrics. This prevented the top layer from getting tangled from the motor .

Pulley–spool geometry was constrained by the servo output interface and packaging envelope. The spool was bonded to the servo horn, and a central through-hole provided a consistent anchoring feature for the actuation line. The line was threaded through this aperture and secured with one to two wraps to maintain preload and constrain the winding trajectory, ensuring that rotation produced repeatable line tracking along the spool path. This anchoring scheme also enabled rapid rethreading and tension adjustment without disturbing the actuator mounting.

The flippers comprised a tendon-routed, segmented TPU architecture. The actuation line was guided through discrete routing nodes, and distal pull propagated through the segment chain to generate a cascading curl. Curvature was localised to compliant hinge regions defined by reduced TPU thickness (≈1.25 mm) between thicker structural sections (≈5 mm), biasing deformation to designed zones while enabling elastic return to the neutral configuration on unloading. Flippers can be seen along the two opposite sides of the dress, along the outer portion of the ankle. Fig 5 and 6 can display its octopus-like movement.

Fig. 2: Front view of Formaflow with hem lifted during walking. The lifted segments increase toe clearance and reveal the intentional layered silhouette.

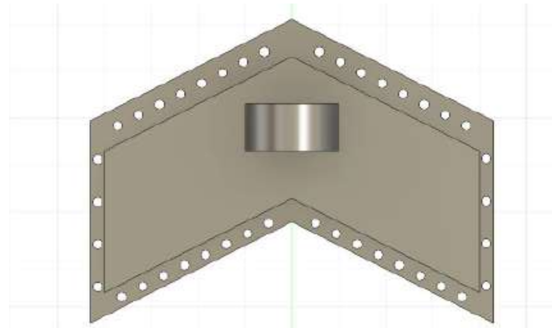


Fig. 3:CAD of the TPU filament pulling attachment. Holes were implemented along the edge to be hand sewn onto the dress. This is one iteration of the design.

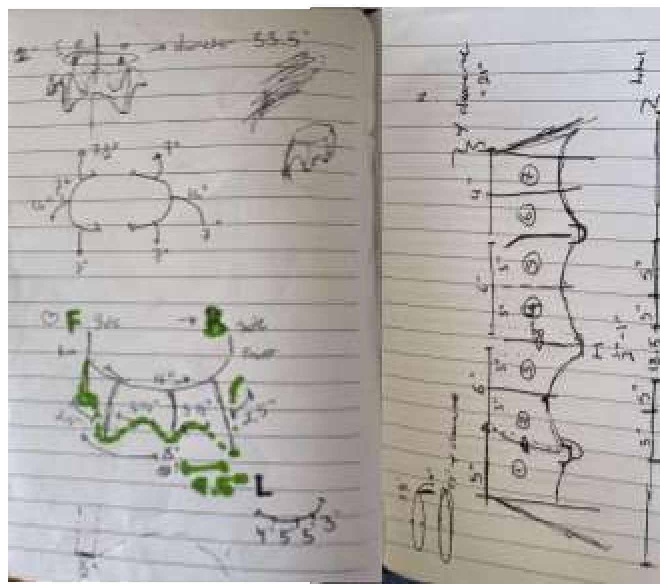


Fig. 4: Load-path sketch showing how pulley forces are routed aligned to the corset while.

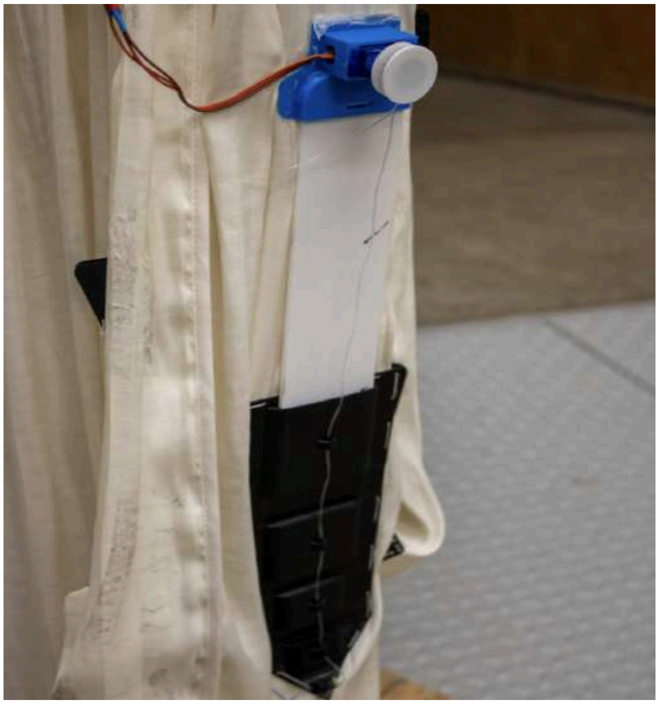


Fig. 5: Entire octopus- like flippers. Along TPU flipper design there are holes that allow the material to be sewed on. The middle white backbone allows for the main mass of the flipper to stay stable when the user is walking. The motor is attached above to keep everything compact and tight.

Fig. 6: Flipper beginning to curl upwards.

C. Fabrication Workflow

Fabrication and textile assembly were conducted in parallel across an iterative prototyping cycle. The process began with establishing a mannequin-based test rig and a baseline corset structure, followed by garment construction and fabrication of pulley mounts, and concluding with electronics integration and refinement of the transmission and line routing. Additively manufactured components were produced on a daily cadence to enable repeated fitting, alignment, and rapid design updates. Each integration session followed a standardised checklist covering line routing, stopper placement, and servo alignment to improve build-to-build repeatability. A bill of materials is summarised in Table II and reports component masses and functional allocation.

TABLE II: Bill of materials (core components)

Table 1: Bill of Materials – Morphing Dress Electronics

Component	Part Number / Description	Qty
Microcontrollers		
Main Controller	Adafruit ESP32 Feather V2 (8MB Flash, 2MB PSRAM, STEMMA QT)	1
Remote Controller	Adafruit ESP32 Feather V2 (8MB Flash, 2MB PSRAM, STEMMA QT)	1
Sensors		
IMU	Adafruit LSM6DSOX + LIS3MDL 9-DOF IMU Breakout	1
Actuators		
Belt Servos	SG90MR Metal Gear Continuous Rotation Servo	4
Flipper Servos	SG90MR Metal Gear Continuous Rotation Servo	2
Display & Interface		
OLED Display	SSD1306 128×64 I2C OLED Display	1
Buttons	Tactile Push Button (6mm)	6
E-Stop Button	Red Emergency Stop Button	1
LED Indicator	3mm or 5mm LED (Red/Green)	2
Power System		
Battery	6V NiMH Battery Pack (2000mAh+)	1
Voltage Regulator	3.3V LDO Regulator (AMS1117-3.3)	1
Interconnect & Hardware		
Protoboard	Perma-Proto Half-size Breadboard	1
JST Connectors	JST-XH 3-pin Servo Connectors (pairs)	8
I2C Cable	STEMMA QT / Qwiic Cable (100mm)	2
Headers	Break-away Male Headers (40-pin strips)	2
Wire	Silicone Wire 22AWG (Red, Black, Signal colors)	5m
Heat Shrink Tubing	Assorted Heat Shrink Kit	1
Mechanical		
TPU Mounts	3D Printed TPU Flexible Mounts for Servos	6
Pulley Posts	3D Printed PLA Pulley Posts	4
Corset Plates	Laser-Cut Acrylic Mounting Plates (3mm)	2
Fabric Attachments	Nylon Webbing & Stitching Thread	1
Fasteners		
M3 Hardware	M3×8mm screws, nuts, standoffs (assorted)	1 kit

Table 2: Bill-of-materials layout and component placement. Printed pulley posts, corset plates, servos, IMU, radio, and battery are shown relative to the dress layers.

D. Material Selection Study

Three thread classes (elastic, rigid cord, and cotton) and two fabrics (lightweight rayon and a midweight cotton blend) were evaluated using small fabric sample pieces prior to full-garment integration. Elastic thread produced uncontrolled recoil and increased tangling, whereas rigid cord introduced higher friction and produced visible ridges beneath the outer layer. Cotton thread paired with the midweight cotton blend yielded smooth sliding behaviour while concealing the routing.

Tape adhesion was assessed across masking tape, painter's tape, and fabric tape. Painter's tape provided the most suitable balance of grip and removability when replaced daily.

E. Textile & Structural Integration

Xochitl Ortega sewed the full dress and designed a structural corset to house electronics and distribute loads. The doublelayer architecture conceals the mechanisms while allowing access to anchor points and routing channels. Stitching patterns were integrated within the printed 'attachment' to provide stability when adding loads. The corset was used to provide clearance between the bi-layers (Fig. 7). The corset increased organization with wiring and ensured the motors would not get interference and tangled. Thread selection was iterated: elastic threads tangled, rigid cords jammed in pulleys, and thin cotton thread provided the best compromise between glide and knot security. Tape was strategically added along lifting threads to form mechanical stoppers and anchors (Fig. 8). These stoppers pinched fabric at precise locations, turned the continuous thread into discrete segments, and prevented over-travel. The result was a more predictable fold geometry and a cleaner visual rhythm during motion. Seam allowances of 10 mm were maintained to form hidden channels for thread routing. A small hatch inside the lining gives access to the electronics bay without exposing hardware to the outside. The mannequin helped with iterative checks to test drape and wrinkle formation after each sewing change, keeping the final garment smooth when idle.

Fig. 7: Corset is flipped upright, showing motor integration and design. Motors were placed in a TPU housing and hand stitched into the base. Denim was used under the corset to provide more stability since it is stiffer and holds more weight.

Fig. 8: A look between the bi-layer: Taped-thread stoppers positioned along lifting lines to pin fold locations and block over-travel, improving symmetry and repeatability.

F. Electronics & Control

Kamron Soltani led electronics and firmware. A compact ESP32 Feather v2 microcontroller interfaces with six SG90MR servos and a wireless receiver ESP via ESPNow. A handheld remote enables three preset modes: walk lift, stair auto-lift, and manual pose tuning. An inertial measurement unit (IMU) LSM6DOX monitors the accelerometer data as well as the gyroscope to trigger stair lifting automatically [4]. Actuation timing per servo was tuned to stagger motion: tiles start first to shorten hemline, then flippers flare outward to refine silhouette. The electronics bay is embedded in the corset (Fig. 9), while the remote UI is shown in Fig. 10. The state machine is summarized in Fig. 11. The radio link uses a simple packet protocol with checksum and sequence number to avoid repeated triggers. The electronics were integrated on a protoboard to ensure durability and integration into wearable fabric. We integrated the electronics into compliant TPU mounts with fabric stitching. For the calibration of each motor, we utilized the manual mode to expose per-servo trims, letting the wearer set asymmetric poses when walking near obstacles. A low-voltage cutoff prevents brownouts that could leave the dress half-lifted. All wiring terminates in JST connectors to ensure that we can debug fast and replace motors when they burn out.

One of the most difficult aspects of this project was finding high torque continuous motors in a small footprint. We tested three different motors, including the SG90 with plastic gears, the small 12V geared motor with an encoder, as well as linear actuators. The original SG90R servo motors provided the highest torque and was able to lift the fabric with the supplied 6V battery supply; however, the repeated load stripped the plastic gear, rendering them inoperable. We switched to the metal version to mitigate this error. The one issue with the motors was feedback, as the continuous servos do not have any encoders. Thus, we had to do ample amounts of experimental testing to see the timing for different patterns, and seeing that the lifting duration was longer than the dropping, as gravity plays into effect. In future iterations, we would like to have a lightweight and non-invasive gearbox with a geared motor or servo with feedback to mitigate this issue, and to perform more designs and morphing shapes of the fabric.

The sensor architecture for the IMU used an LSM6DSOX 6-axis accelerometer and gyroscope on the corset, wired over I²C to the ESP32 Feather V2 and streamed via ESP-NOW to a separate receiver node for classification. On the receiver, the receiver_logger.py script deploys a rolling buffer of vertical acceleration, classifies 20-sample windows as WALKING, ASCENT, or DESCENT using tuned mean and standard-deviation thresholds, and then passes these labels through a 20-slot voting system so only strong majorities trigger a "stairs up" or "stairs down" event. A minimum inter-event interval and a final full-buffer sanity check keep the stair detector from double-firing or reacting to random bumps, while the printed packet stats and compact activity labels make it easy to tune thresholds live on the wearer.

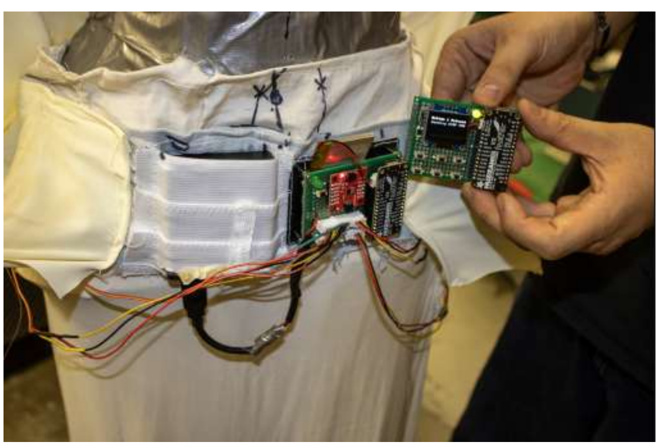


Fig. 9: Corset-integrated electronics bay with cable routing and strain relief for servo leads. The housing is hidden between garment layers.

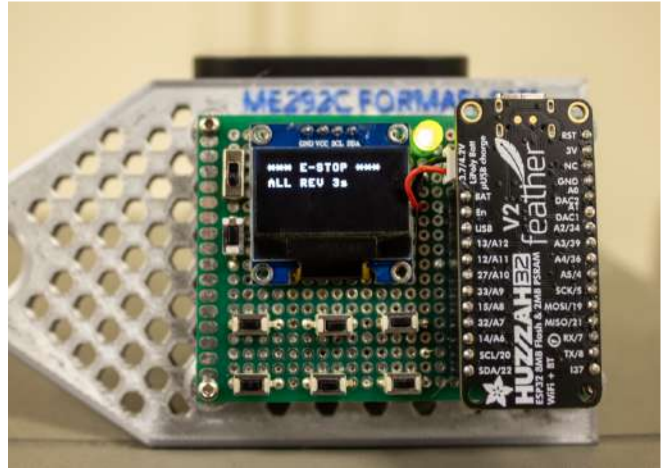


Fig. 10: Handheld remote UI with presets for walk lift, stair auto-lift, and manual tuning. Latched buttons simplify mode confirmation.

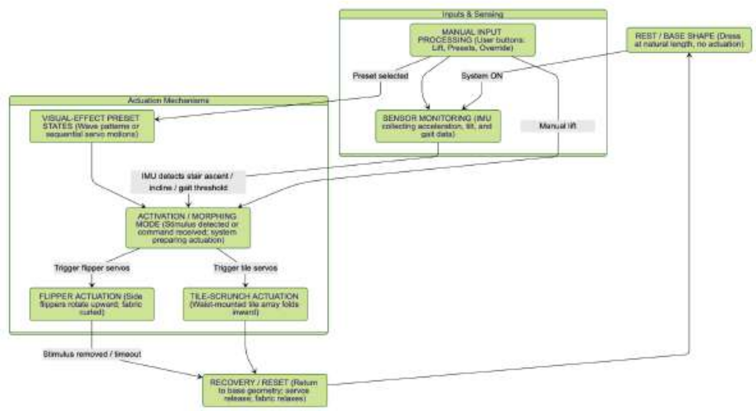


Fig. 11: State machine of the dress.

G. Software Architecture and Timing

The firmware is organized into three layers: (1) a sensing layer that filters IMU data with a complementary filter; (2) a mode manager that latches user inputs and applies safety interlocks (e.g., blocking lifts when battery voltage is low); and (3) an actuation scheduler that issues staggered servo commands. Timing profiles were stored as small arrays allowing quick iteration during testing.

The transmitter code running on the handheld remote manages user input debouncing, connection monitoring, and command dispatch over ESP-NOW. A 0.128×0.064 m OLED displays connection status and the currently active mode, giving the wearer real-time feedback without needing to look at a laptop. The remote polls six buttons at 100 Hz with software debouncing set to 200 ms to prevent accidental double-triggers when the wearer is moving or adjusting their grip. Button 5 is mapped to the primary "lift" command (cmd=1), which triggers the forward stagger sequence, while the physical e-stop button sends cmd=2 to immediately reverse all motors for 3 seconds, providing a fail-safe if fabric gets caught or the wearer needs to abort mid-lift. An onboard LED blinks at 2 Hz when the ESP-NOW link is down and stays solid when connected, which became critical for debugging range issues during live demos when the wearer walked more than 10 meters from the electronics bay.

The ESP-NOW protocol itself is connectionless and broadcast-based, so the firmware adds a thin reliability layer by periodically sending keepalive pings (cmd=0) from the transmitter and updating the connection flag based on whether the receiver ACKs within the 1-second poll window. This simple handshake prevents the system from silently failing if the wearer walks out of range or if interference from stage lighting disrupts the 2.4 GHz band. Each command packet is a single byte, which keeps air time under 1 ms and latency below 50 ms end-to-end, meeting the real-time constraint that the dress should respond within a human reaction time so the wearer can interactively adjust their silhouette while walking.

The staggered actuation scheduler is the heart of the morphing choreography. Instead of driving all six servos in unison, the firmware starts the four belt servos (which pull the hemline tiles upward) immediately, then stops the two flipper servos (which flare the silhouette outward) 2 seconds earlier to let the belt motors finish shortening the dress without interference. This asymmetric timing was tuned empirically by filming the dress from the side and counting frames until each fabric section reached its target position, then encoding those durations as BELT_DURATION = 4.0 and FLIPPER_DURATION = 2.0 at the top of the receiver script. Storing timing profiles as compile-time constants rather than loading them from a file or EEPROM made it trivial to re-flash new values during rehearsals without needing a full rebuild or configuration tool. In future iterations, we plan to replace the hardcoded sleep calls with a more flexible event-driven scheduler that can queue overlapping moves or smoothly interpolate between poses, but for a first prototype the blocking-sleep approach was simple, deterministic, and easy to debug with a logic analyzer on the PWM lines.

H. Safety & Comfort Considerations

Safety checks ensure servos do not over-travel past the taped stoppers; current limits are enforced in firmware by bounding pulse widths. Wires are strain-relieved in the corset bay to avoid skin contact. Padding was added where PLA could press against the torso, and ventilation gaps prevent heat buildup from the battery.

I. Calibration & Tuning

Calibration and testing were performed on a custom mannequin test rig constructed to match the wearer's body geometry. The mannequin enables repeated fitting and controlled, off-body evaluation.

Testing proceeded from subsystem trials to full-garment integration. Morphing mechanisms (tile lift and flipper curl) were first evaluated on small fabric samples to establish viable routing and deformation behaviour, then transferred to the garment's functional base layer (lining and corset) where actuators and transmission elements were mounted. The outer layer was reserved for visual finish and was integrated after the base-layer mechanisms demonstrated stable operation. To support rapid iteration, the garment incorporated quick-access features (zippers and velcro) that allowed disassembly and adjustment without disrupting the overall routing layout. The entire bi-layer was similar to a sheet that fastened around the perimeter of the dress with velcro.

Calibration focused on synchronising morphing behaviour around the garment. Each actuator was mechanically zeroed, and line lengths and pre-tension were manually equalised across channels to ensure that tiles and flippers initiated deformation at a consistent point in the motion cycle, producing uniform lift and drape. Control timing was then refined in discrete increments to improve motion smoothness. All adjustments were logged against a fixed mannequin pose to support reproducible comparisons and rollback to prior configurations.

J. Build Failures and Iteration

Early prototypes exposed failure modes that motivated substantive changes to actuator placement and transmission design. An initial architecture placed all actuators at the waist; however, flipper actuation in this configuration primarily produced vertical lift rather than curl. Effective curling required a localised rigid support about which the compliant flipper could develop a moment. The actuator was therefore repositioned lower on the garment and paired with a rigid support structure to provide a stable curl backbone, seen in Fig. 5, and to decouple curling from gross upward translation.

A second concept attempted to keep the waist-mounted actuation by introducing chevron-style interlocking elements intended to self-stiffen under tension. This design iteration of attachment can be seen in Fig. 3. The elements were designed to first engage into a rigid chain and then serve as the backbone for curling. In practice, the mechanism proved unreliable on a deformable, flowing textile surface. The relative plane of the interlocking features varied during motion, causing the elements to collapse and overlap rather than make the intended face-to-face contact required for engagement. Iteration on this approach confirmed that consistent interlocking demanded a more controlled planar constraint than the garment could provide. A square attachment worked best at providing these features (Fig. 12)

Transmission failures also arose in the lifting lines. Early routing produced tangling and line “beading,” prompting repeated adjustments to thread choice and anchoring. In the tiled hem mechanism, a first implementation relied on successive tiles contacting one another to propagate lift. This was replaced with a staged strategy using discrete beads placed along the line at calibrated offsets relative to each tile’s guide feature. Under tension, each bead contacted its corresponding guide sequentially, producing a controlled cascade without requiring tile-to-tile collisions. The beads were prototyped as small line fixtures formed from zip ties and hot glue, and this modification substantially improved the consistency of the lift and crease formation.

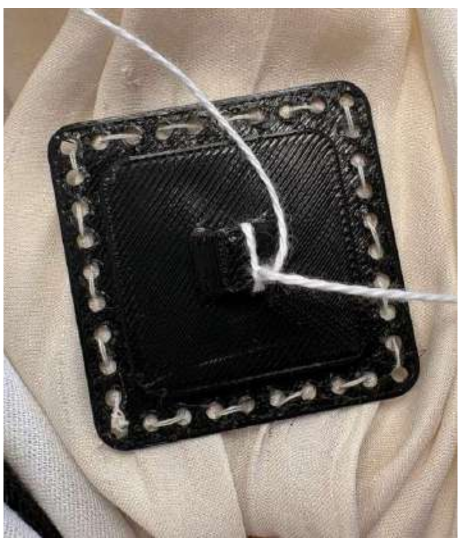


Fig. 12: Square attachment that gets pulled which creates the scrunching silhouette. Sewn into the base.

VI. RESULTS

Figures 13–16 show the deployed system. Quantitative metrics are summarized in Table I and expanded in Table III. Results are organized per use case and instrumented measurements.

TABLE III:

Actuator Group	Lift Duration (s)	Drop Duration (s)	Phase Offset (s)
Belt Tiles (4×)	4.0	3.0	0.0
Flippers (2×)	2.0	1.5	0.0
Hold Phase	2.0	1.5	+2.0 (tiles), +2.0 (flippers)
Total Cycle Time	4.0	3.0	—

Table 3: Formaflow function requirements

A. Walking Mobility

In walk-lift mode the hem shortened by approximately 120 mm, eliminating ground contact on level surfaces. Four lifting servos split the load, reducing per-servo current spikes and enabling smoother transitions. Figure 13 captures the lifted pose while descending stairs. This trial was done without the top layer to ensure the electronics were consistent and sensing the descending motion.

Figure 14 shows the baseline silhouette with mechanisms hidden at a neutral position. Once lifted, the flippers will start curing, causing a change of silhouette, seen in fig. 15, and scrunching will occur in the middle portion, causing lifting and distance from the ground. Wearers reported improved confidence when stepping forward and appreciated the visible layering created by the staged lift. Acoustic noise remained low because the staggered profile avoided simultaneous high-torque starts. Front face photo of the morphing dress can be seen in Fig 16.

Fig. 13: Stair ascent sequence showing auto-lift activation, hem shortening, and flipper curl for toe clearance.

B. Reliability and Repeatability

The taped-thread strategy reduced fold drift between trials. Over 20 consecutive lifts, fold variance at three landmarks stayed within 8 mm. Servo duty cycles remained below thermal limits, and no cables loosened thanks to strain relief in the corset bay. Battery endurance was approximately 35 minutes of continuous actuation or several hours of intermittent use typical of a walk-through.

Fig. 14: Rear view in the normal configuration, showing baseline hem length and hidden mechanisms.

Fig. 15: Actuation timing profile: tiles lead, followed by flippers, then a hold phase to maintain silhouette before a controlled return.

Fig. 16: Full project photo on the custom mannequin with electronics concealed inside the corset.

Fig. 17: Snapshots from fabric and electronic integration

VII. DISCUSSION & LIMITATIONS

Formaflow demonstrates the feasibility of hemline morphing as a combined mobility and expressive capability within the constraints of a wearable garment. The system couples two complementary deformation modes, hem shortening via tiled lifting lines and outward deflection via tendon flippers, to address hazards such as toe catch during walking and stair ascent and ground contact in wet or dirty environments. A central outcome of this work is that deformation repeatability in textile driven mechanisms can be strongly influenced by small transmission level interventions. In particular, discrete line fixtures or beads. In this case, prototyped from zip ties reinforced with hot glue enabled staged engagement along the tiled hem. Under tension, each bead contacted its corresponding guide feature in sequence, producing a controlled cascade of lift without relying on tile to tile collisions. This modification substantially improved the consistency of crease formation and symmetry across repeated cycles relative to earlier routing strategies.

Several trade offs remain. The bead based engagement strategy improves predictability but introduces additional line hardware and may reduce environmental robustness if fixtures shift, snag, or degrade under moisture, abrasion, or repeated wear. Future iterations should replace ad hoc bead constructions with low profile, mechanically locked fixtures, for example molded elements or stitched constraints, that preserve calibrated engagement while improving durability and washability. More generally, transmission reliability remains sensitive to routing tolerances and tension. Achieving synchronous onset of tile lift and flipper curl required manual equalisation of line length and pre tension across channels. This adds calibration overhead and can drift with textile stretch or repeated donning. Reducing this burden is therefore a key engineering priority, either through self tensioning mechanisms, more constrained fabric integrated channels, or transmission architectures that are less sensitive to small line length errors.

A further limitation is the lack of direct position feedback at the actuator and spool. Although servo commands specify a target angle, the effective line payout under load can vary due to compliance, friction, and occasional line slip, leading to drift in fold placement and timing across channels. Incorporating encoders, either by using actuators with integrated position sensing or by adding compact encoders at the spool or output stage, would enable closed loop verification of motion, detection of slip events, and more reliable synchronisation between lifting and flipper sequences. Encoder feedback would also support calibration free operation by allowing the system to re zero and correct for gradual drift over time, rather than relying on manual tension matching.

Actuation choices impose additional constraints. The selected micro servomotors provided adequate performance for the present textile mass and routing friction. However, scaling to heavier fabrics or larger strokes will require stronger actuators or increased mechanical advantage, with associated penalties in bulk, acoustic output, and power draw. Mass concentrated at the waist, notably the battery pack, occasionally shifted during vigorous motion, indicating the need for improved load distribution and retention within the corset structure.

Sensing and control are intentionally lightweight and constitute a further limitation. Stair intent is inferred from a simple pitch threshold heuristic, which can be confounded by abrupt posture changes or atypical gait. More robust intent recognition will likely require distributed sensing and sensor fusion approaches that remain compatible with garment level constraints on comfort and concealment. Acoustic output was acceptable in indoor testing, but performance contexts may impose stricter requirements, motivating quieter actuation and improved isolation.

Claims regarding comfort, social perception, and the intentionality of motion are based on informal feedback rather than controlled studies. A structured protocol with larger cohorts, standardised tasks such as walking, stair ascent/descent and quantitative measurements of lift would strengthen the evidence base and clarify the relationship between deformation choreography and perceived aesthetics.

Despite these limitations, the development process yielded several actionable design lessons. A custom mannequin matching the wearer's geometry enabled repeatable off body calibration and accelerated iteration without repeated fittings. Integrating stitching apertures directly into printed components reduced assembly overhead and improved mechanical integration between textile and structure. The project indicates that garment morphing performance depends as much on transmission level constraints, anchoring, routing, and staged engagement, as on actuator selection. These insights define clear near term directions. These include hardening the bead based engagement mechanism for environmental durability, reducing calibration effort through more self consistent tensioning and routing, adding encoder feedback for drift resistant synchronisation, and miniaturising electronics and actuation while preserving repeatable motion.

VIII. FUTURE WORK

Three directions are prioritised. First, sensing: distributed flex or capacitive sensors along the hem could estimate ground proximity and enable predictive lifting, complementing the IMU based trigger with local context. Second, acoustics and form factor: replacing geared servos with quieter actuation, such as twisted string mechanisms, could reduce audible output and expand suitability for performance and gallery settings. Third, personalisation: a mobile interface could allow wearers to create motion palettes and store them as selectable profiles, shifting morphing from a fixed behaviour set to a configurable design parameter.

Sustainability is also a key consideration. Future iterations should explore bio based printable materials and modular construction designed for disassembly, enabling maintenance and laundering while supporting end of life separation and recycling.

IX. CONCLUSION

Formaflow establishes hemline morphing as a practical mechanism for improving mobility while preserving expressive, intentional motion in a wearable garment. Using a double-layer architecture with embedded actuation, tiled lifting lines, and calibrated line engagement, the system reshapes the hem to support walking, stair ascent, and traversal of wet or dirty ground while maintaining a clean baseline silhouette when idle. This work highlights that repeatable garment morphing depends not only on actuator selection, but also on transmission design and constraint placement that govern how fabric deforms.

The resulting platform provides a foundation for responsive apparel that integrates more robust sensing, quieter and slimmer actuation, and user configurable motion profiles, enabling garments that adapt to real world contexts while communicating intent through controlled deformation.

REFERENCES

[1] L. Yao, J. Ou, C.-Y. Cheng, H. Steiner, W. Wang, and H. Ishii, “Biologic: biological skins as material for multi-sensory interactions,” Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction, pp. 413–414, 2013.

[2] S. Kim, C. Laschi, and B. Trimmer, “Design of a biomimetic soft robotic arm inspired by the octopus,” Bioinspiration & Biomimetics, vol. 8, no. 2, p. 025005, 2013.

[3] L. Devendorf and K. Ryokai, “Programming the material interface,” Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, pp. 5757–5768, 2016.

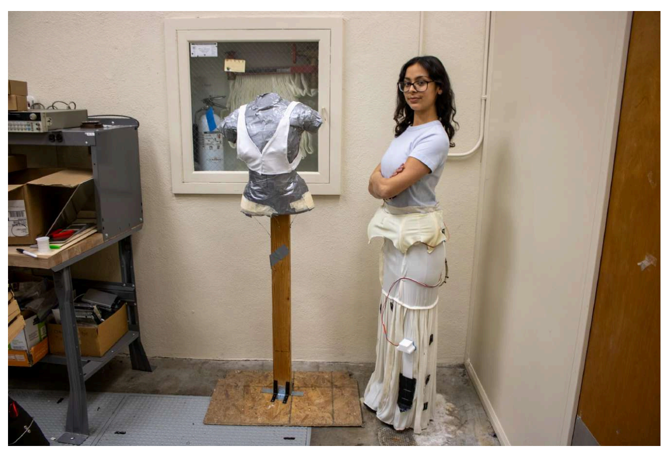
[4] S. Majumder and M. J. Deen, “Wearable sensors for remote health monitoring,” Sensors, vol. 20, no. 5, p. 1324, 2020. [5] O. Tonet, V. P. Truong, M. Hara, T. Wada, and M. Asada, “A soft wearable robot for assisting human locomotion using twisted string actuators,” in 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2017, pp. 3720–3727.

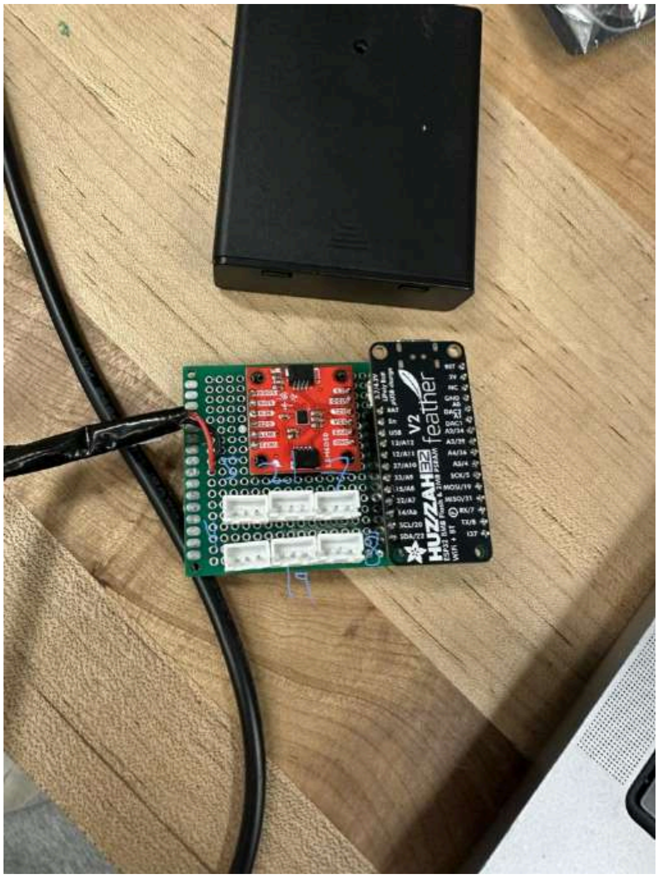
[6] P. Martins, A. Lima, A. Esteves, and C. Ribeiro, “Responsive textiles for distributed sensing and actuation: a materials review,” Advanced Functional Materials, vol. 30, no. 52, p. 2007086, 2020.

APPENDIX


1829


Berkeley
Engineering




V2
feather