Rapidly Prototyping Robots with Plate and Reinforced Flexure (PARF) Mechanisms

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***Abstract*— We present Plate And Reinforced Flexure (PARF) fabrication, an inexpensive rapid fabrication technique for robot mechanisms inspired by the Smart Composite Manufacturing (SCM) used in VelociRoACH [1] and RoboBee [2] designs. PARF extends SCM to larger sizes at low costs. We used PARF to develop a meter scale hexapedal robot, BigANT [3], which design we made publicly available. Manufacture of BigANT requires minimal tooling – foam board, tape, a saw blade, and a knife; the chassis costs $<$ $20 US in materials, encouraging its use in research, education, and recreation. We present a study of PARF joints, showing several variations spanning a range of fabrication effort and mechanical properties. PARF promises the possibility of quickly and inexpensively building robot mechanisms for tasks as the requirements arise, rather than relying on pre-fabricated robot bodies.**

I. Background

Computer controlled additive manufacturing is revolutionizing the world of design prototyping. For all its power, versatility, and popularity for devices on the scales of 1 to 10 cm, additive manufacturing has played a limited role in fabrication of larger devices and robots. Here we aim to provide open-source robotic devices usable by hobbyists, school teachers, and first responders working out of the back of a van. Several factors hinder the use of "3D printers" here: (1) printing functional mechanisms typically requires high precision multi-material printers – high tooling costs; (2) multi-material printing requires additional processing with solvents, raising logistics and safety requirements; (3) construction of meter scale devices would require many hours of build time, defeating the purpose of rapid prototyping. Subtractive methods can operate considerably faster – and none faster than laser cutting and engraving. A substantial benefit of laser cutting is that laser cutter designs that require low tolerances can often be cut by hand if the laser is unavailable. We were thus lead to mechanism design methods that employ laser cut plates and flexures, such as SCM.

SCM uses rigid plates connected by flexible hinges to create millimeter and centimeter scale articulating mechanisms quickly and inexpensively. For example, the fabrication of the 8 cm long hexapod in [4] could be completed in less than one hour, costing under $1 US. SCM and related methods have been used to make several robotic prototypes, such as a 3 cm six-legged hexapod walker [5], a larger 10 cm hexapod [6], a 20 cm jumping robot [7], a 1 cm scale hovering robot fly [2], a centipede [8], and other structures such as linked chains [9]. Assembly can be simplified by utilizing pop-up structure techniques [9].

SCM involves the laminating laser cut plates of a rigid material to sandwich a flexure material, then folding the plates to produce three-dimensional linkages. The rigid material is typically fiberglass [5], poster-board [4], or carbon fiber [9], and the flexible material is typically a polymer film. While enabling the development of a rich collection of robot mechanisms, so far the maximum size of robots manufactured by SCM has been limited.

It is not surprising that scaling up SCM designs geometrically by an order of magnitude does not lead to functional mechanisms, as structural properties do not scale in a simple way. For example, according to Euler beam theory, a cantilever plate made twice as long and wide, but none thicker becomes four times softer in bending. Extended lengths also increase the misalignment that comes from angular play at the joints between the plates. A combination of new materials, components, and design heuristics must be made for larger scales.

To make low cost, larger scale robots we developed "Plate-and-Reinforced-Flexure" (PARF) mechanisms. In our designs, rigid plates are made from inexpensive materials such as foam board, corrugated plastic, and cardboard; joints are constructed with fiber-reinforced tape. The tooling required to work these materials is minimal: scissors, a hack-saw blade and straight edge metal ruler will do. For improved results, a laser cutter and/or hot-melt adhesive may be used as well. We present several designs of structures and joints possible with PARF, and report quantitative results of tests for strength and durability. Such variety, with well understood properties, enables PARF designs to satisfy diverse mechanical functional requirements.

PARF mechanisms are readily actuated with servomotors. The servomotors and associated power electronics are by far the most intricate and expensive parts of PARF robot systems. We chose to encapsulate this complexity in modular, reusable components [3] making it easy and inexpensive to modify designs and adapt to changing needs.

The efficacy of our method is demonstrated using a $90\,\mathrm{cm} \times 60\,\mathrm{cm}$ walking robot (See Figure 1) with six individually actuated one degree of freedom legs. We were able to rapidly iterate through different mechanisms to improve the design, often changing designs and testing them on a daily basis. Through this rapid evolution we reached a platform that allows for walking in both indoor and outdoor environments up to $30 \pm 3\ \mathrm{cm/s}$ with a foot clearance of approximately 4 cm, and turning at $4.2°/\mathrm{s}$.

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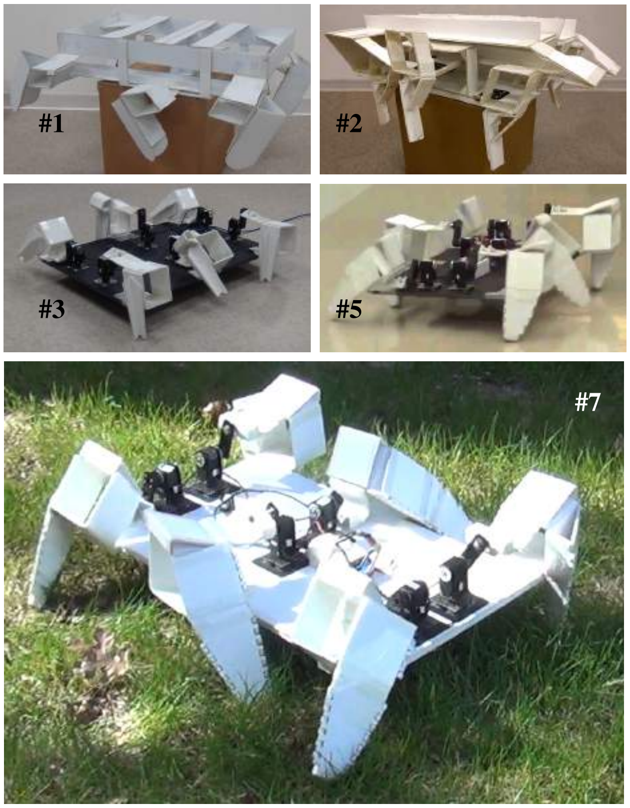

Fig. 1. Design iterations of the BigANT PARF hexapod. Chasses #1, #2, #3, #5, and #7 are depicted above. #3 was the first capable of walking. #7 could successfully traverse outdoor terrain.

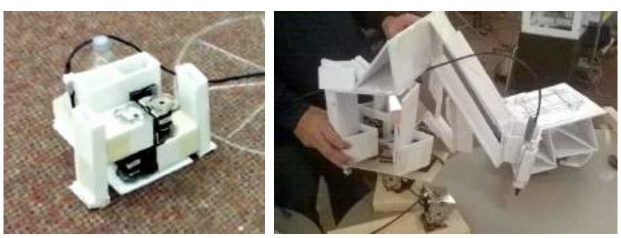

Fig. 2. PARF robots from a classroom. [left] A crawling robot using reciprocating limb motions. [right] A robot arm drawing a square.

Furthermore, PARF was employed extensively in a robotics design class[1]. Students were challenged to use PARF to build functional walking robots and arms (see Figure 2).

II. PARF as SCM for the Meter Scale

For PARF's joints and structural elements, we selected materials that were inexpensive, lightweight, and easy to work, yet could effectively withstand the physical demands of the application.

A. Material selection: Rigid plates

We considered candidate rigid materials of foam board (Elmer's Products Inc. $50.8\,\mathrm{cm} \times 76.2\,\mathrm{cm} \times 0.72\,\mathrm{cm}$ foam board), corrugated plastic board (SABIC Polymershapes Coroplast COR-2436 $91.4\,\mathrm{cm} \times 61.0\,\mathrm{cm} \times 0.40\,\mathrm{cm}$), and corrugated cardboard (Home Depot $55.9\,\mathrm{cm} \times 53.3\,\mathrm{cm} \times 0.3\,\mathrm{cm}$ box). The price per square meter of foam board is \$14.03 US (OfficeMax), of corrugated plastic is \$22.21 US (DisplayShops), and of corrugated cardboard is \$1.05 US (Home Depot). Thus all of the candidate materials are available at convenient sizes and low prices.

We quantified each material's resistance to bending via its mass-specific flexural rigidity. This is the ratio $EI/M = (Pl^3)/(3\delta M)$, which assumes an Euler cantilever beam bending model [10] with load P, length l, deflection δ, and sample mass M. We tested single layers of each material by securing $5\,\mathrm{cm} \times 20\,\mathrm{cm}$ samples to a table with a massive plate, allowing $15\,\mathrm{cm}$ of overhang, and taping a test weight across entire width of the distal end. Deflections were measured using a ruler at 2 loads (14.0N and 25.2N). For non-isotropic materials, we tested both strong and weak directions (i.e. along the corrugations and across the corrugations).

TABLE I
Bending Stiffness for PARF Rigid Materials (N=3)

Material	**M/A** (g/m^2)	**EI/M** (m^3/s^2)
Plastic (strong)	720 ± 20	30.0 ± 2.0
Plastic (weak)	720 ± 20	10.3 ± 2.0
Cardboard (strong)	620 ± 20	38.3 ± 2.5
Cardboard (weak)	620 ± 20	31.0 ± 2.5
Foam Board	640 ± 20	110 ± 20

Table I shows foam board is superior in terms of mass-specific rigidity, and was therefore selected. The other two materials may be useful in specific circumstances. Cardboard can be used as an economical alternative if cost dominates other considerations. Corrugated plastic can be used if resistance against delamination and water damage are a priority.

B. Material selection: Flexure material

The flexible material used in PARF joints needs to be compliant in bending, stiff with respect to tensile loads, and resistant to tearing. It should also easily attach to the plates.

We chose to use a composite – fiber reinforced tape. Using tape allows us to skip the curing and lamination steps required in the SCM process, which require specialized equipment and additional time. This comes with the limitation that only one side of the flexure material may be used for adhesion to plates.

Fiber tape is available in bidirection and unidirectional varieties. The unidirectional tape is stronger in longitudinal tension, but tears lengthwise under crosswise tension. In our mechanisms, we used both 5 cm wide bidirectional fiber tape (3M Scotch #8959; 26 kN/m strength; 6% yield strain) and 1 cm wide unidirectional fiber tape (3M Scotch #898, 66.5 kN/m strength; 5% yield strain). The current market prices for the bidirectional and unidirectional tapes are 42 and 27 cents US per meter respectively (Amazon.com).

C. Joint design

Figure 3 shows five hinge-joint designs. These differ in fabrication time and loading bearing capabilities. Many

[1] "Hands on Robotics," a senior level class taught at the University of Michigan

additional designs underwent preliminary tests; all were outperformed by one or more of those shown.

Minimally, a joint consists of one piece of tape spanning the gap between the two plates. Careful alignment of the plates minimized undesired freedom in the joint. Joints often failed by the foam board's paper exterior delaminating from its foam filling. To resist these failures we tightly wrapped unidirectional tape fully around the foam board on both sides of the spanning tape (see Figure 3); we refer to this as "frapping", a term that comes from lashings (AnimatedKnots.com). A layer of tape on the backside of the joint, which we refer to as "backing", also helped postpone failure.

Our designs are characterized by two parameters: (1) range of motion: 0° to 180°, 90° to 270°, and 0° to 360° joints, and (2) rigidity and durability with respect to off axis loads.

The 0° to 360° joint has interwoven strips of tape and only has moderately more play than that of the other two configurations. Note that no pin joint between physical plates can allow for 360° rotation – axis motion on the order of plate thickness is *required* for achieving this range of motion.

Making stiffer, more robust joints can come at the expense of increased construction time, which is closely related to the number of pieces of tape in the design. We found that frapping and backing operations made the joints stronger, at moderate cost in terms of construction time (see Figure 4).

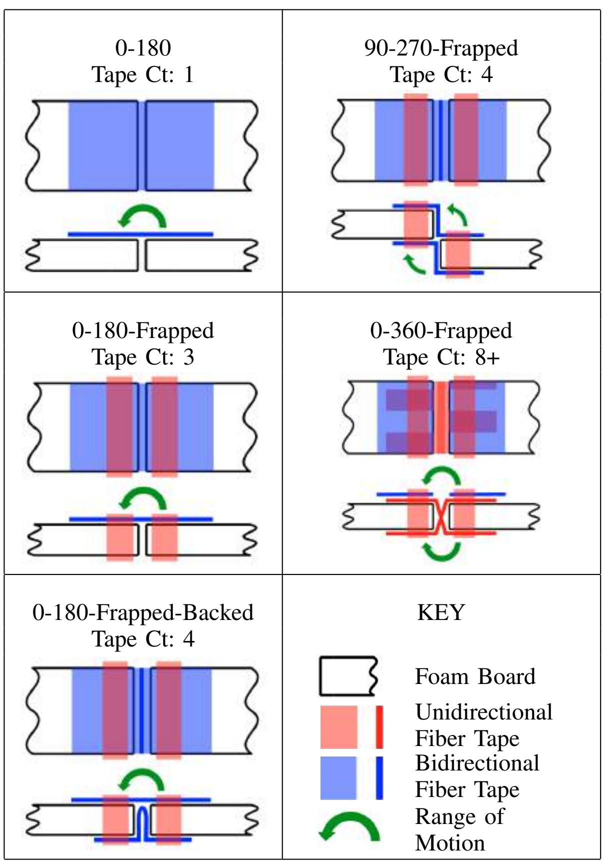

Fig. 3. Five hinge designs are depicted with top (above) and front views (below). Naming scheme comprises the range of motion, and any taping operations such as frapping and backing. The number of tape pieces used ("tape count"), directly affects the fabrication time. All joints are shown in their 180 degree position.

D. Repeated load tests

The most common form of failure of PARF joints we observed in our robots was delamination, which occurs most readily with torsional loads. The sensitivity of the joint to such off axis torque is itself a function of its angle at the time of loading. To compare our designs, we chose to load each joint in torsion at bend angles of 90° and 180°.

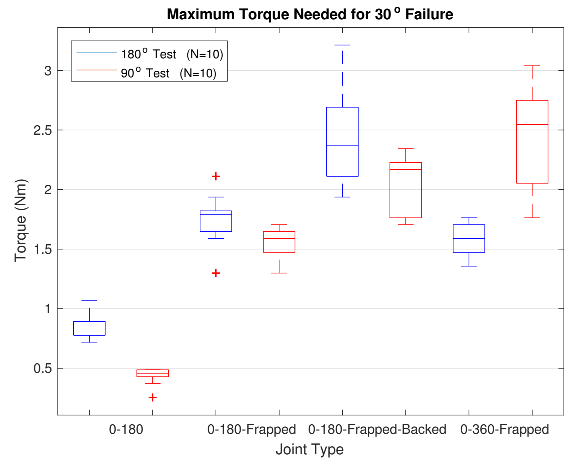

Fig. 4. Failure torques by joint type and testing angle (blue 180°; red 90°; $N = 10$ for each boxplot). The results show the added benefit of frapping and backing operations. Note that the joints with a 180° range are most durable in the 180° position, whereas the 360° joint, and a 90° to 270° joint (which results are not shown) were most durable in the 90° position.

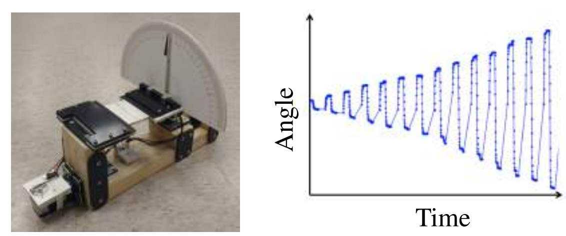

Fig. 5. Repeated load testing rig. We held joint samples (white, center) with plastic clamps (black rectangles) and commanded a servomotor (hidden behind white indicator dial) to torque a clamp around the axis perpendicular to the joint axis. We incremented torques from 0 Nm by 0.06 Nm, executing 1 back and forth cycle at each torque level and holding each torque for 3 seconds to allow joint to move to its mechanical limit. We stopped the test when the joint rotated more than 30° off axis, defined as "joint failure" (typical trial, right).

We built $N = 10$ of each joint out of $7.6\,\text{cm} \times 7.6\,\text{cm}$ foam board squares, which we fixed in plastic clamps constructed of $0.64\,\text{cm}$ ABS, $2.5\,\text{cm}$ away from the joint edge. Each clamp had a transition zone of thinner $0.16\,\text{cm}$ ABS extending $1.25\,\text{cm}$ closer to the joint edge and reducing stress concentrations that could tear the plates. Clamps allowed some translation in the direction of insertion, but otherwise completely constrained the samples. With one clamp stationary, the other was torqued with a servomotor (Dynamixel MX64, Robotis Inc) which also provided an angle measurement (tested accurate to better than 1°). Gradually increasing the "max torque" of the motor we twisted joints back and forth, maintaining each direction long enough for the joint to twist to a stationary position (see Figure 5). We calibrated our torque measurement using test masses of up to $1\,\mathrm{kg}$ hung from an arm of length $29\,\mathrm{cm}$ and torqued against gravity by the servomotor until it stalled.

After applying both frapping and backing to the joints, any additional taping appeared to have rapidly diminishing returns. At that point, the plate material itself was the main source of failure, limiting the joint's ability to resist torsion.

We compared the "standard" 0-180-Frapped-Backed joints built with both types of tape, to "simplified" joints built using only bidirectional fiber tape, subjecting both types of joints to the test as above (N=30). The 2-sided Kolmogorov-Smirnov test (`scipy.stats.ks_2samp` SciPy 0.13.3) gave $p < 0.001$ showing that samples are significantly different. Standard joints had IQR 70% smaller than that of the simplified joints, and median 10% higher failure torque. Results justify the use of both types of tape. Under repeated constant loads at 75% of the mean failure torque, standard joints (N=5) failed after 3252 ± 12 (mean, std) cycles.

E. Structural member design

PARF techniques can be used to build structural members with improved load bearing capabilities compared to single plates. Some structures easily built include layered plates, fin-stiffened plates, and prisms (see Figure 6), with construction techniques described below. Note, the way in which the shear is transferred from one plate to another strongly affects rigidity in shell structures. All of these structures can be built with tape to transfer shear; hot melt adhesive (Surebonder All Purpose Glue Sticks) can be used to improve results.

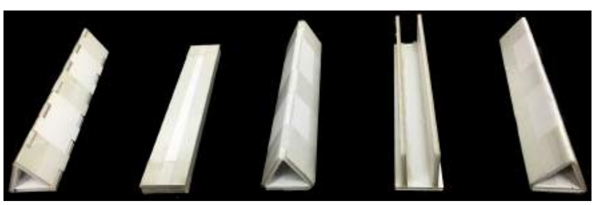

Fig. 6. Structural members made using PARF techniques. [left to right] Notched prism, layered plates, cut-folded prism, hot-glued fins, and crush-folded prism. Each was made from a $30.5\,\mathrm{cm} \times 15\,\mathrm{cm}$ piece of foam board.

Layered plates are weakest structurally, but most compact. They can be either glued together across the faces or taped together around the outside edges. Fins, or stiffeners, can be used to dramatically reduce bending of a plate in a specific direction. They are best applied by gluing onto a base plate. Alternatively, notches can be cut into the plates and taped together. Triangular prisms are particularly good at resisting both torsion and bending. They can be made by folding or cutting notches in the plates. Plates can be folded in two ways: (1) crushing the foam board along a line; (2) partially cutting through the foam board, leaving one surface as a hinge.

F. Tooling

One of the great strengths of PARF is its minimal tooling requirement. The rigid plates for all of the mechanism we present can be cut with a straight edge and hacksaw blade. With the addition of scissors or knife for cutting tape, the toolkit is complete. Plates can be cut by laser cutter instead (ours is a Universal Laser Systems PLS6.150D, 150 W CO_2 laser). A laser cutter improves precision especially for intricate patterns. It also lowers fabrication time of both the cutting and assembly phase.

One key advantage is that the laser can be calibrated to score the plate cutting through one face and the intervening foam while leaving the other face intact, allowing the intact face to be used as a hinge provided it is reinforced with tape. Aligning multiple joints this way reduces assembly time.

We scored both sides of the foam board during laser cutting by flipping the plate and using alignment tabs. Our procedure was: (1) cut alignment slots in foam board; (2) affix foam board to alignment tab in the laser cutter; (3) score first side; (4) flip and re-affix plate to alignment tab; (5) score second side; (6) release part; (7) fold and tape part. Cuts on both sides created the outline; cuts made on only one side created joints (see Figure 7).

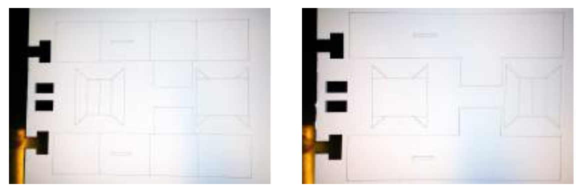

Fig. 7. Fabricating a PARF mechanism is made easier through laser cutting by partially cutting through the foam board. A pattern is used with side A (left) and side B (right). The acrylic fixture is used to align the foam board for cutting on both sides (left).

We successfully built a hexapod leg mechanism using both manual and automatic tools, namely a hack saw and a laser cutter (see Figure 8). Using the laser cutter, we made the leg in about 45 minutes; using the hacksaw, in about 150. Note, these times were for a design with notches, which are particularly time intensive with the hacksaw. The legs made from both methods had comparable quality. We tested (N=3) joint samples in torsion with plates cut by hacksaw and did not find any noteworthy difference in failure torque.

The fabrication time of a single folded PARF mechanism using the laser cutter is similar to that that reported for SCM mechanisms [4], proving our method allows for equivalently rapid prototyping despite the vastly different scale.

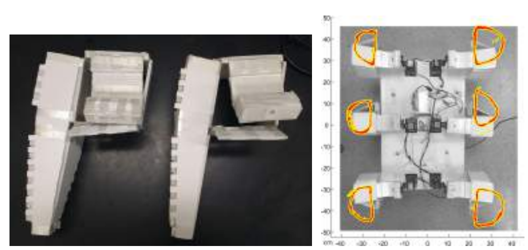

Fig. 8. [left panel] Comparable quality mechanisms can be built from either a hacksaw (left) or a laser cutter (right). Using the laser cutter took less than half the time. [right panel] foot trajectories of chassis #6, collected while walking using a Qualisys motion tracking system at 120Hz, given relative to chassis frame.

III. Building a Meter-Scale Hexapod with PARF

Using PARF techniques, we built a 90 cm long hexapedal robot (76 cm base plate with legs extending 7 cm on both ends). The chassis, including legs and drive-train, cost less than $20 US, and required less than six hours of labor to build. PARF allowed us to rapidly iterate through 40 design changes, of them 25 drive mechanism design changes, and 7 complete chassis re-builds (see Figure 1), improving robot performance inexorably over a short time period. The current robot can walk, steer, and turn in place on both indoor and outdoor surfaces, testifying to its viability as a legged platform.

A. Mechanism Design

We attempted to use only two motors in early iterations of the design, based on scaled up versions of Berkeley's VelociRoACH robot [1]. However, we were unsuccessful in making the drive train rigid enough (in structure and joint-play) to bear the load of the robot from a single motor on each side. This lead us to our current design, which consists of six identical leg mechanisms mounted on a base plate, with a motor for each.

For walking, we chose to utilize an alternating tripod gait wherein anterior and posterior ipsilateral legs move in phase with the contralateral middle leg. This gait is the one used by most hexapedal animals when moving at moderately high speeds within their speed range [11]. The motion of each leg is theoretically determined by the 1-DOF kinematic constraints of its linkage (see Figure 9) to give a roll angle of over 60° in mid-swing and an unloaded clearance of over half a leg length. The individual leg moves vertically in the sagittal plane around mid-stance, then rapidly swings sideways and outward at the end of stance to recycle forward. This motion was verified through testing (See Figure 8).

1) Actuation: To complete the legged locomotion platform required power circuitry, actuation and control – complex, yet well understood problems. We encapsulated the electronics in modular components that can easily be attached and released from the chassis, allowing rapid replacement of faulty parts and rapid design iteration. Our actuators were high-end hobby servomotors (Dynamixel MX64, Robotis Inc). Each servomotor drove a plastic crank connected via a ball bearing to a bolt inserted into a pillow-block which is part of the PARF-built leg mechanism input link. The motors were attached to the base of the chassis with ModLock quick locking connectors [12] (see Figure III-A.1). To transfer the load effectively from the hard ModLock components to the soft foam board base, we used a transitional layer of 1/16 inch ABS plastic[2].

A four cell lithium polymer battery was used to power the motors through an under-voltage protection circuit. Our computing platform was an embedded platform (Intel Edison) running Linux.

[2]The ModLock is not free to use; for the open source version of our design the ModLock is replaced by two MDF plates.

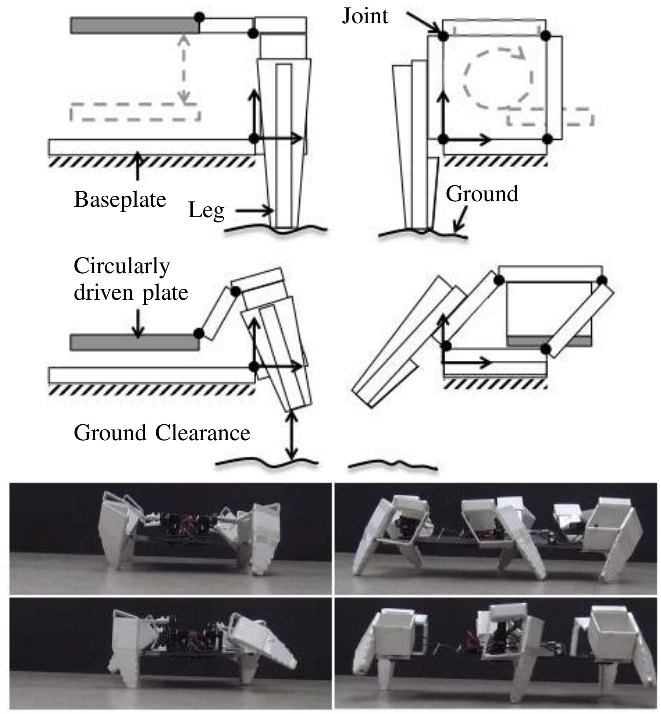

Fig. 9. The leg mechanism is depicted in the stance position (top) and the swing position (bottom), as seen from the front (left) and side (right). The drive link (grey) is driven by the motor in a circle.

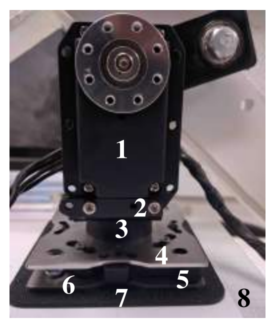

Fig. 10. Module assembled. (1) servomotor (2) steel bolt plate (3) stack of circular ABS spacers (4) top steel Modlock plate (5) flexible ABS Modlock spider (6) bottom steel Modlock plate (7) transitional ABS layer (8) foam board base (9) transitional ABS layer (not shown) (10) MDF block (not shown). Wood screws connect the bottom Modlock plate through to the MDF block.

The electric motor based actuation modules we chose for our design are an expedient compromise – heavy and expensive high-end servos, which run counter to the low cost, low weight philosophy we promote. Future work will explore the space of actuation system modules, including lower cost electrically driven modules and pneumatic actuators. Pneumatics could dramatically reduce weight and cost per DOF in complex robots.

The control software for our robot uses the Python `pyckbot` library which was developed for the 2010 ICRA Planetary Challenge [13] to ease the development of modular robot control software.

B. Chassis cost

The cost of fabricating each iteration of the hexapod chassis was low. In the case of chassis #4, the total materials required were two $76\,\text{cm} \times 102\,\text{cm}$ pieces of $0.5\,\text{cm}$ thick foam board boards, one $76\,\text{cm} \times 51\,\text{cm}$ piece of $1.3\,\text{cm}$ thick foam board board, $150 \pm 25\,\text{cm}$ of bidirectional fiber tape and $280 \pm 50\,\text{cm}$ of unidirectional fiber tape. At the current market prices (Amazon.com), this is a total of $18.01 US in foam board and $\$1.36 \pm 0.24$ US in tape – less than $20 US altogether. The cost of the more complex modular components, were approximately $300 US per leg. Thus, over 98% of the material cost is preserved from one design iteration to the next and making such robots ideal for classrooms and hobby applications.

The cost of our chassis appears to scale reasonably well compared to SCM on the centimeter scale. An $8\,\mathrm{cm}$ long SCM hexapod is estimated to cost $1 US [4]. Our robot is roughly ten times larger, or $\times 10^3$ larger in mass, but only $\times 20$ as expensive. Our robot chassis is very inexpensive compared to similarly sized robot mechanisms which use more familiar materials. For example, the same chassis built using 20 gauge perforated steel sheets would cost upwards of $125 US (MetalsDepot.com).

C. Performance

We measured walking speeds of chassis #4 as a function of crank-shaft rotation speed. The robot was brought up to full steady state speed on indoor linoleum tiling floor and timed over a $300 \pm 10\,\mathrm{cm}$ distance using video collected from a stationary camera. Applying motor speeds of 15, 25, and 32 rpm, resulted in a walking speeds of $0.15\mathrm{m/s}$, $0.21\mathrm{m/s}$, and $0.30\mathrm{m/s}$, all $\pm 0.03\mathrm{m/s}$, respectively. Chassis #5 was able to walk at a nominal 42 rpm, do a full turn-in-place in 86 seconds, and turn-while-walking with a turn radius better than $170\,\mathrm{cm}$. The astute reader may wonder at the relative difficulty of turning with these robots; this is a topic of ongoing research in our lab.

We tested chassis #7 in an outdoor environment (see Figure 1), where it navigated uneven terrain with steps up to approximately $4\,\mathrm{cm}$. Additionally, #7 successfully demonstrated walking with a failed front-right limb while the rest of the limbs continued their programmed alternating tripod gait. These tests demonstrate a promising robustness to environmental and design uncertainty.

D. Open source design

We hope to encourage broad use and experimentation with PARF robots. The reader who wishes to build the hexapod described herein may find the design files at https://github.com/BIRDSLab in the `BigANT` repository and the `pyckbot` software library in the `pyckbot` repository. Assembly tutorial and additional information are in the supplemental video attached to this paper.

IV. Benefits and Limitations of PARF

PARF mechanisms face limitations with respects to mechanism strength and durability, and have difficulty limiting play over large distances due to local deformations and low tolerances. Both of these issues can be partially overcome with supporting structures and parallel linkages. As functional requirements for force and precision become more demanding, PARF designs may be altered to use other materials. In that case, foam-board PARF mechanisms may still perform an important role in prototyping.

PARF mechanisms offer a number of advantages compared to metal and hard plastic mechanisms. With PARF a large and useful design space can be explored at a small cost in time, money, and tooling. Building PARF mechanisms is approachable for novice designers, and is routinely taught to undergrads with no mechanical design background. Only a minimal level of 2D CAD skill is required, and no knowledge of CAM. Mechanisms can often be repaired by splinting and taping, and new features can be prototyped easily and tested before design files are changed.

We consider the greatest strength of PARF its ability to create and refine customized robotic mechanisms without requiring the logistic support structure of a research lab or industrial R&D department. The impact of PARF will be greatest for those with access to fewer resources and less of an industrial base upon which to rely. Whether it is rescue workers at a remote disaster site, students learning about robots in a low income school district, fresh college graduates founding a robotics start-up company, a disaster response team working out of an air-dropped container, or the very first humans exploring the surface of Mars – PARF would allow them to build useful robots quickly, inexpensively, and with only a few tools.

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