

FINAL REPORT

Crab-like Legged Robot for Accessing and Classifying Munitions in Surf Zones

SERDP Project MR19-1369

OCTOBER 2020

Kathryn Daltorio
Nicole Graf
Yifeng Gong
Alexander Behr
Case Western Reserve University

Distribution Statement A

This document has been cleared for public release



This report was prepared under contract to the Department of Defense Strategic Environmental Research and Development Program (SERDP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 12/10/2020		2. REPORT TYPE SERDP Final Report		3. DATES COVERED (From - To) 7/3/2019 - 7/3/2021	
4. TITLE AND SUBTITLE Crab-like legged robot for accessing and classifying munitions in surf zones				5a. CONTRACT NUMBER 19-P-0052	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Daltorio, Kathryn A.; Graf, Nicole; Behr, Alexander; Gong, Yifeng				5d. PROJECT NUMBER MR19-1369	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Case Western Reserve University 10900 Euclid Ave Cleveland Ohio 44106				8. PERFORMING ORGANIZATION REPORT NUMBER RES221686	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research & Development Program 4800 Mark Center Dr Suite 16F16 Alexandria, VA 22350				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR19-1369	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Tasks in munitions response such as remote surveys, retrieval, and disabling of potentially hazardous unexploded ordnance require traversal of amphibious terrain. Surf zones, areas of the ocean with shallow water, are a particularly critical area. Accessing unexploded ordnance in these areas may be prioritized to prevent them from reaching land. Mobile robots have the potential to make these tasks safer and more efficient. The main objective of this project was to determine the degree to which crab-like legs increase the force required to dislodge the robot, effectively increasing weight. This required developing amphibious robot platforms with crab-like legs, and a lab wave tank test set-up. In addition to characterizing static gripping behavior, it was important to validate that the gripping legs could also locomote on natural terrain in both controlled lab substrates and in local beaches. We also show preliminary sensor integration. We can build on the leg designs in future work to determine the simplest effective legs and create a more developed platform to compare trafficability with wheeled robots in surf zone terrains.					
15. SUBJECT TERMS Bio-inspired robotics, locomotion in sand, legged robotics, amphibious munition response, surf zones					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 51	19a. NAME OF RESPONSIBLE PERSON Kathryn Daltorio
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 216-408-3474

Abstract.....	1
Executive Summary	2
Introduction	2
Objectives	3
Technical Approach	3
1. Robot Design	3
2. Evaluation in lab wave tank.....	4
3. Locomotion testing on various substrates.....	4
4. Leg-Embedded sensors	4
Results and Discussion	4
Implications for Future Research and Benefit.....	9
Final Report: SEED Crab-like legged robot for accessing and classifying munitions in surf zones	11
Objective.....	11
Background	12
Materials and Methods.....	17
1. Robot Design.....	17
2. Dactyl Design	21
3. Robot Waterproofing	21
4. Evaluation in lab wave tank	22
5. Leg-Embedded sensors.....	25
Results and Discussions	26
Grip Characterization	26
Freshwater Beach Testing	31
Summary Discussion	33
Conclusions and Implications for Future Research/ Implementation.....	35
Works Cited.....	37
Appendix A: Total Wave Test Displacement Performance	42

LIST OF FIGURES

	Page
Figure E1. Amphibious hexapod robot uses crab-like dactyls (white) to walk from dry sand to sand submerged in water.....	2
Figure E2. In preliminary evaluations, we compared 11 different robot feet. We chose the crab-inspired foot 8, which will be referred to as Dactyl 8, due to its promising performance in both maneuverability of the robot and the ability to grip. Throughout this paper, we compare the effectiveness of the original capped foot, the flat foot, and Dactyl 8. See [26] for more detail on the dactyl design.....	3
Figure E3. The force required to dislodge the robot with Dactyl 8 with and without pulling inward during the stance. When pulling into a grip stance, vertical force significantly higher than the weight is required, especially in submerged sand.	5
Figure E4. The displacement results of Wave Test 1. The displacement between the capped foot, flat foot, and Dactyl 8 are due to the cross-sectional areas of the foot. The smaller the cross-sectional area, the better the foot can dig into the sand. This increase in grip ability helps the robot hold its place in the environment. There was no measurable displacement with Dactyl 8.	5
Figure E5. The position of the robot in Wave Test 2 during 10 waves in the lab tank with a large grip. The displacement amplitudes are greatest with the original leg with the cap, are lessened with the original uncapped foot, and are the smallest with Dactyl 8. The displacements between each wave along with the total displacement from before the first wave to the end of the last wave also follow this trend. The displacements for all feet are in Appendix A.....	6
Figure E6. The displacement per wave averaged over 30 waves (reset every 10 waves) for each grip and foot type, shows that crab-like dactyls decrease displacement even when waves dislodge robot.....	7
Figure E7. The robot's speed was evaluated on several different substrates (n=15): hard smooth linoleum tile (A), dry sand (B) wet sand, (C) and submerged sand with 25.4mm of water above sand line which is enough to completely submerge feet of the robot (D), and rock bed (E).....	7
Figure E8. Sensor embedded leg and data from leg on hard surface showing consistent peaks that correspond with stance.....	8
Figure E9. Amphibious robot concepts that can be used to respond to munition. Such robots can be deployed from either a boat or from a beach.....	10
Figure 1. Amphibious hexapod robot uses crab-like dactyls (white) to walk from dry sand to sand submerged in water.....	11
Figure 2. Our climbing robots grip substrates with many different substrate/mechanism combinations, including the first to use micro-structured adhesive feet for climbing vertically and then later inverted, first to demonstrate exterior transitions with adhesive feet, and first to	

climb inverted using spines on a 1DOF robot [56], a concept which was later demonstrated with an 18 DOF robot [57]. Distributed inward gripping was developed based on observations of beetles arranging feet (blue arrows) to generate opposing forces [56].....	16
Figure 3. A. Clearance range of crab-like robots over obstacles of varying diameter. The ratio of 1:1.5 for the femur compared to the tibia and dactyl allowed the robot to navigate over the widest range of obstacles. B. The assembled Sebastian robot. Each leg was made of PLA by a 3D printer and was equipped with three servos (Savox SV1270TG) to provide high torque (486.1 oz-in, 3.43Nm). Mass of servo is 56 g. Compared to the Hexy robot (torque per mass is 0.0223Nm/g), Savox SV1270TG has 0.061Nm/g.....	18
Figure 4. A The path of each joint of the 7 bar linkage that makes up each leg of the Klann 1 robot. (Position A is (0,0), position B is (36,-9), position C is (30,42)) B. The modeled version of the Klann 1 robot C. The main frame of Klann 1 is 3D printed (PLA). Legs are acrylic boards (¼ inch) cut by laser cutter (Epilog Fusion Pro 48). D. Compliance of the Klann 1 that consists of one slot and two springs (225.9N/m).....	19
Figure 5. A The path of each joint of the 7 bar linkage that makes up each leg of the Klann 2 robot. (Position A is (0,0), position B is (43,0), position C is (26,34)) B. The assembled version of the Klann 2 robot.	20
Figure 6. In preliminary evaluations, we compared 11 different robot feet. We chose the crab-inspired foot 8, which will be referred to as Dactyl 8, due to its promising performance in both maneuverability of the robot and the ability to grip. Throughout this paper, we compare the effectiveness of the original capped foot, the flat foot, and Dactyl 8. See [26] for more detail on the dactyl design.	21
Figure 7. (A) Hexapod robot before waterproofing shows white dactyls, blue HEXY legs, orange wires that connect joint actuators, and grip test harness (black loop) (B) Amphibious robot has waterproof electronics box (clear), and silicone and marine grease coatings.....	22
Figure 8. The grip motions are shown here in air without sand for visibility. At the onset of stance (A) the distance between contralateral pairs of legs is approximately 20 cm. Gripping motions result in the distance being reduced to 74% for the small grip (B), 66% for the medium grip (C), and 63% for the large grip (D) with corresponding changes in dactyl angle.....	22
Figure 9. The grip tests were conducted 30 times in each sand with each foot type while the robot performed one of the four grips of interest. The results are recorded as maximum forces as percentages of the robot's weight.	23
Figure 10. The grip test setup for the Klann 1 robot. Here, the compliance in the spring is fully stretched in order to have the maximum effect on the grip.....	23
Figure 11. At the red line, the water is 76.2mm deep. This water level reaches the bottom of the waterproof box on the robot. The water is 155.6mm deep where the piston is. The piston's initial depth is 25.4mm at 20°. The waves are 63.5mm at the red line and are generated 298.5mm away from the front feet of the robot. The board connected to the piston that is used to generate the waves is 228.6mm x 301.6mm. The stroke of the piston is 152.4mm. The piston was powered with an air tank at 100 psi. The waves were then generated at 3.2 Hz for four waves. After that, the robot's total absolute displacement was recorded.	24

Figure 12. Wave tank provides consist size waves to demonstrate effectiveness of dactyls to resist displacement.	24
Figure 13. Constructed wave tank for in lab testing to better control variables that could alter the results of our testing. This tank was made with 1 inch acrylic to combat the forces from the sand and water, and is 60 in long by 24 in wide by 36 in tall. The frequency of the wave generator for this tank is 0.27 Hz.	25
Figure 14. Sensor embedded leg and data from leg on hard surface showing consistent peaks that correspond with stance and swing.	25
Figure 15. After 30 trials in each configuration in (A) dry sand (B) wet sand (C) submerged sand, boxplots show that gripping is more effective with crab-like dactyls and in submerged sand.	26
Figure 16. The displacement results of Wave Test 1. The displacement between the capped foot, flat foot, and Dactyl 8 are due to the cross-sectional areas of the foot. The smaller the cross-sectional area, the better the foot can dig into the sand. This increase in grip ability helps the robot hold its place in the environment. There was no measurable displacement with Dactyl 8.	27
Figure 17. The position of the robot in Wave Test 2 during 10 waves in the lab tank with a large grip. The displacement amplitudes are greatest with the original leg with the cap, are lessened with the original uncapped foot, and are the smallest with Dactyl 8. The displacements between each wave along with the total displacement from before the first wave to the end of the last wave also follow this trend. The displacements for all feet are in Appendix A.	28
Figure 18. The displacement per wave averaged over 30 waves (reset every 10 waves) for each grip and foot type, shows that crab-like dactyls decrease displacement even when waves dislodge robot.	29
Figure 19. The robot's speed was evaluated on several different substrates (n=15): hard smooth linoleum tile (A), dry sand (B) wet sand, (C) and submerged sand with 25.4mm of water above sand line which is enough to completely submerge feet of the robot (D), and rock bed (E).	30
Figure 20. A. Hexy holding its position on rocky beach B. Hexy walking into the water at sandy beach.	31
Figure 21. Klann 2 robot walking at 1 meter depth in shallow inland lake.	32
Figure 22. Amphibious robot concepts that can be used to respond to munition. Such robots can be deployed from either a boat or from a beach.	36

LIST OF TABLES

	Page
Table 1. Comparisons of the Different Robots Utilized	17
Table 2. Specifications of the Sebastian Robot	18
Table 3. Specifications of Klann 1	20
Table 4. Specifications of Klann 2.....	20
Table 5. Measurement of Hexy Robot.....	31
Table 6. Measurement of Klann 2.....	33
Table 7. Speed of Different Robots on Dry Sand	30

ACRONYMS AND ABBREVIATIONS

Aka	also known as
Cm	centimeters
DIG	Distributed Inward Gripping
DOF	Degree of Freedom
e.g.	for example
Fig.	figure
G	grams
Gf	gram force
Hz	hertz
Kg	kilograms
LIDAR	Light Detection and Ranging
M	meters
mA	milliamperere
Mm	millimeters
Mph	miles per hour
N	newtons

N	number
NH	New Hampshire
Nm	newton-meter
ONR	Office of Naval Research
Oz-in	ounce inch
PLA	Polylactic acid
Psi	Pound-force per square inch
P-value	probability
SEED	SERDP Exploratory Development
SERDP	Strategic Environmental Research and Development Program
SVM	Support Vector Machines
UXO	Unexploded Ordnance

Abstract

Keywords: mobile robots, biological-inspiration, amphibious legged robotics

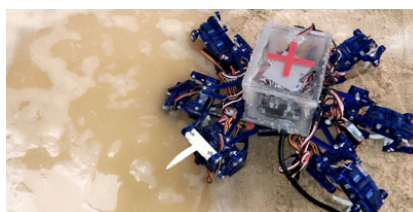
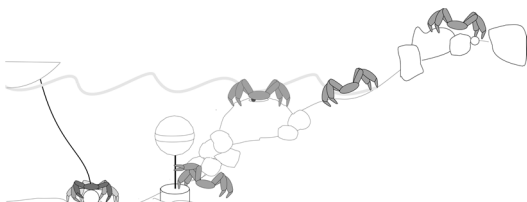
Introduction and Objectives: Tasks in munitions response such as remote surveys, retrieval, and disabling of potentially hazardous unexploded ordnance require traversal of amphibious terrain. Surf zones, areas of the ocean with shallow water, are a particularly critical area. Accessing unexploded ordnance in these areas may be prioritized to prevent them from reaching land. Mobile robots have the potential to make these tasks safer and more efficient. However amphibious locomotion is challenging in surf zones. The design space is limited by sinking in sand at high body weights, and disruptions from waves at low body weights.

The main objective of this project was to determine the degree to which crab-like legs increase the force required to dislodge the robot, effectively increasing weight. This required developing amphibious robot platforms with crab-like legs, and a lab wave tank test set-up. In addition to characterizing static gripping behavior, it was important to validate that the gripping legs could also locomote on natural terrain in both controlled lab substrates and in local beaches. We also show preliminary sensor integration. We can build on the leg designs in future work to determine the simplest effective legs and create a more developed platform to compare trafficability with wheeled robots in surf zone terrains.

Technical Approach: Inspired by biological crabs, we built and modified legged robots (mass 1kg to 4kg). In controlled lab tests, we compared pointed, crab-like dactyls with traditional rounded robot feet and compared effects of gripping the ground by moving legs inward from stance position. We measured maximum vertical grip forces with a digital force gauge and a constant speed winch. With visual tracking, we measured displacement due to waves generated with a hydraulic piston. We validated the robot outdoors in freshwater lake waves.

Results: We show that by using a curved sharp dactyl and pulling the feet inward, the effective weight can be increased by a third in wet submerged sand. The sharp dactyls can eliminate travel from waves that would otherwise displace the robot several centimeters and reduce travel due to larger waves. The dactyls can walk consistently on rocks and sand, but the speed is less than with original rounded feet (likely due to slip on hard surfaces and sinkage on sand). In outdoor tests, we demonstrated walking into waves that crash over the body, and walking submerged at depths of approximately 1m. We also show that sensors can be integrated into the feet to collect ground contact data which consistently responds to load distributions.

Benefits: This work expands the design space for future amphibious legged robots with reduced weight. This is expected to help amphibious robots better navigate waves, handle increased payload and deploy from aerial vehicles. Selectively grasping ground could also enable ultra-efficient gaits in which robots exploit wave forces. Applications of such robots could include gathering samples along waterline, accessing sites with hazardous materials, and potentially using additional legs to move or disable individual pieces of unexploded ordnance.



Crab robot concepts for surf zones (left) and crab robot platform with pointed dactyls during amphibious testing (right).

Executive Summary

Introduction

Amphibious mobile robots can be valuable tools for future munitions response, enabling remote surveys, retrieval, and disabling of potentially hazardous unexploded ordnance. In particular surf zones (areas of the ocean with shallow water) are critical, as described in the SERDP munitions response statement of need (MRSON-21-C1). Accessing unexploded ordnance in surf zones can limit their exposure to air, wave forces, land animals, and humans.

However, sand is a challenging terrain for existing autonomous robots. Granular media flow and cohesion depends on pressure, velocity, and moisture. Failure modes range from stalling due from excessive sinkage into the sand to becoming dislodged by the hydrodynamic forces from waves. A key design parameter is robot weight; a heavy robot can better withstand relatively large wave forces but a light robot can more efficiently traverse dry sand. Here, our goal is to demonstrate the feasibility of using legs to grasp the ground to increase the effective weight of the robot (Fig. E1) while still enabling locomotion in sand.

Prior amphibious robots have explored many different locomotion strategies. Wheels and wheel-legs can traverse many outdoor terrains [1]–[5] with simple rotation. Models exist to relate grain properties to velocity [6]. Articulated legs can step over larger obstacles and select footfall locations [7]–[10]. Crabs and other arthropods have inspired robots with various morphologies and control strategies[11]–[23], but have not exploited the ability of crab-like legs to anchor in the sand. Our working hypothesis is that the crabs may be using their legs differently than land animals (which could partially explain their distinct morphology [24]), specifically to anchor themselves to the ground. Compared with existing amphibious robots [1], [3], [5], [11], [18], [25], crab-like legs could be key to developing smaller surf zone robots.

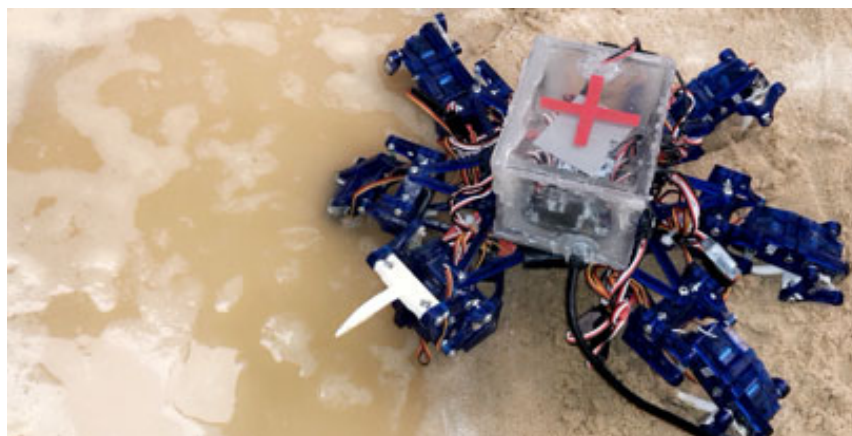


Fig. E1. Amphibious hexapod robot uses crab-like dactyls (white) to walk from dry sand to sand submerged in water.

Objectives

The goal of this SEED project is to evaluate the degree to which it is feasible for a robots' legs to anchor the body to the ground by grasping the terrain. Our hypothesis is that by selectively creating inward tangential forces between opposing legs, crabs grasp the ground for traction greater than their weight when needed to be able to anchor during waves, and release for efficient wave-riding and swimming. Is anchoring in wet sand compatible with walking on dry sand? What specific design components are essential? To answer this, we

1. Developed amphibious platform robots with several different leg and foot designs
2. Evaluated anchoring of robots in lab wave tank, which we build during this phase
3. Demonstrated legged walking on range of substrates, including freshwater beaches
4. Demonstrated embedded sensors in the legs, which may enable smarter gaits for heterogeneous terrain.

Technical Approach

1. Robot Design

The biological inspiration for our work is crabs, which can traverse sandy, rocky and wave-swept wet and dry terrain that current robots cannot cross with their many degree of freedom (DOF) legs. Like crabs, an articulated robot can independently control each joint. For expediency, the first articulated robot platform was based on waterproofing a commercial off the shelf metal gear “Hexy” robot from Arcbotics. Subsequently, we built a second articulated platform with actuators with higher torque to weight ratio, referred to as “Sebastian”. These robots have 6 legs each (two stable tripods) but the legs could be duplicated to more closely mimic the 10 legs of crabs.

These robots are controlled to walk with alternating tripod gaits, in which at least three feet are always on the ground (aka in stance) while the other three feet swing to their next position. This is a typical gait used by many hexapod animals and robots. The novelty in this project is that typically the stance feet are stationary with respect to each other, whereas here at the beginning of stance the feet are pulled inward to develop forces tangent to the substrate. Thus, a small fraction (similar to a coulomb friction coefficient) of those tangential forces is available to resist disruptive forces normal to the substrate.

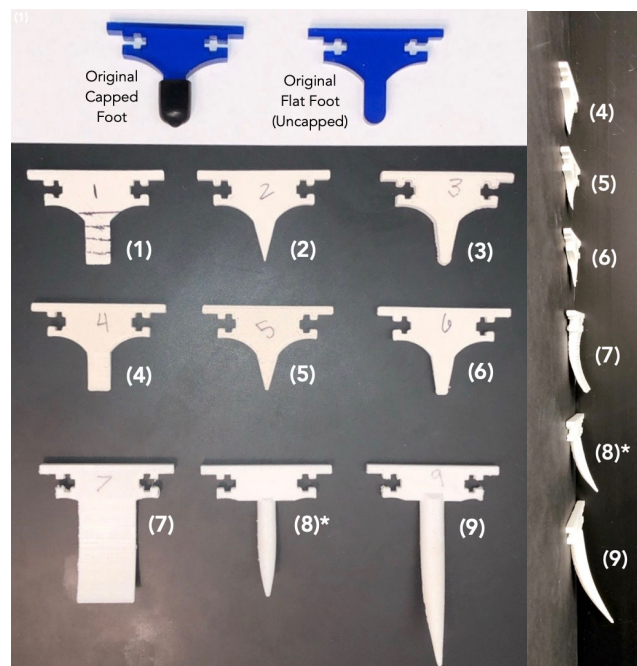


Fig. E2. In preliminary evaluations, we compared 11 different robot feet. We chose the crab-inspired foot 8, which will be referred to as Dactyl 8, due to its promising performance in both maneuverability of the robot and the ability to grip. Throughout this paper, we compare the effectiveness of the original capped foot, the flat foot, and Dactyl 8. See [26] for more detail on the dactyl design.

A critical element of the robot design is the shape of the feet (Fig. E2). In crabs, the most distal segment of the leg is called the dactyl and it has a characteristic pointed shape. Typically, robots for walking on smooth hard surfaces have rounded feet so that they can contact the ground at one angle and roll to another angle. We 3D printed several foot shapes and tested them on the Hexy robot. For walking, the dactyls have to be proportionally sized. To engage with the sand, the best feet were curved with tapering circular cross sections, similar to crab dactyls.

Additionally, because actuators can become a point of failure or interfere with electromagnetic sensing, we have built legged platforms with reduced actuated Klann mechanism legs. Klann mechanisms are a linkage that transforms rotational motion from a single drive servomotor into elongated steps while keeping the center of mass of the robot low to the ground. In this way, one central servomotor can control a number of legs from a protected chassis.

2. Evaluation in lab wave tank

We built a plexiglass tank and filled it with Pavestone Natural Play Sand. The tank is waterproof so that we can evaluate dry sand, wet sand, and sand submerged in water.

Vertical Grip Force Test: The robot was placed in the sand, then moved feet into either reset (no grip) or small, medium, or large grip stance. Then a constant velocity winch pulled the robot vertically up with a digital force gauge. The maximum cable tension during the pull up motion was recorded. During the course of this project, we have increasingly automated the test set up to speed data collection with python scripts.

Wave Testing: Waves were generated in the tank with a compressed air piston (controlled with an Arduino) attached to a flat partially submerged surface. The robot was placed on the sand in the water. For different configurations, the same number of waves were applied to the robot. In the first test, the set position of the piston was manually supported and only the total displacement of the robot was measured. These waves were sized such that with dactyls, no displacement occurred. In the second test, the piston was supported by a bracket and the displacement was tracked with open source vision tracking software Tracker [<https://physlets.org/tracker/>].

3. Locomotion testing on various substrates

Because it is important that the anchoring legs and dactyl still be able to achieve locomotion, we evaluate the locomotion performance across several substrates.

4. Leg-Embedded sensors

Small magnets and associated hall effect sensors were embedded in the legs. Six axis data were collected while the robot was walking and gripping on different environments.

Results and Discussion

Finding 1: Crab-like feet increase grip force generated. Of nine different feet fabricated, Dactyl 8 was most promising in preliminary tests. Thus, the standard original Hexy feet (in blue on top of Fig. E2) were removed and replaced with six of Dactyl 8 for detailed comparison. In detailed comparisons, this shape of dactyl enabled inward motions to create larger forces. Because of the

pointed and curved shape, the feet sink into the sand more and the weight of the sand above assists in resisting disruptive normal forces. The similarity of Dactyl 8 to that of the dactyls of crabs suggests that biological crabs use these same effects.

Finding 2: Inward gripping in sand increases anchoring forces, especially in submerged sand where effective weight is increased by approximately one third. When dactyls are added to the legs, the inward motions of the feet can be used to dig into the substrate resulting in a greater resistance to vertical disruption forces. Both dactyl geometry and the degree of inward motion in stance contribute to this effect, which we have published in a conference [26] and are revising for a journal [27]. Combined, these two effects can enable the robot to resist forces up to 153% of the robot's weight (with a large grip with Dactyl 8) in submerged sand. The averages in dry sand for the reset position, small grip, medium grip, and large grip obtained averages of 103%, 105%, 112%, and 113%, respectively, Fig. E3. In wet sand, these values changed to 105%, 119%, 120%, and 123%. Dactyl 8 performed the best in submerged sand with averages of 105%, 125%, 134%, and 138%. The variation of results for Dactyl 8 is greater because the dactyl would sometimes grip very well, and other times fail to get its feet fully into the sand. Even with this variation, improvement is statistically significant. The increase is expected to be especially valuable in wet and submerged sand because this is where hydrodynamic forces from waves are likely to disrupt robot.

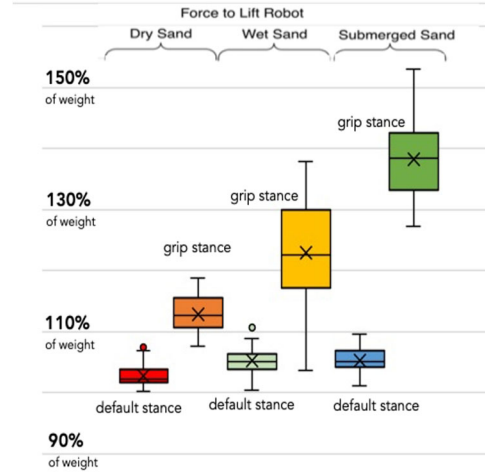


Fig. E3. The force required to dislodge the robot with Dactyl 8 with and without pulling inward during the stance. When pulling into a grip stance, vertical force significantly higher than the weight is required, especially in submerged sand.

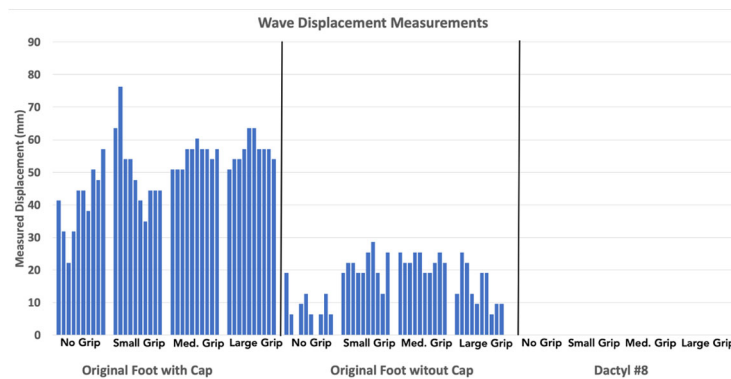


Fig. E4. The displacement results of Wave Test 1. The displacement between the capped foot, flat foot, and Dactyl 8 are due to the cross-sectional areas of the foot. The smaller the cross-sectional area, the better the foot can dig into the sand. This increase in grip ability helps the robot hold its place in the environment. There was no measurable displacement with Dactyl 8.

Finding 3: Dactyl feet can eliminate displacement from small waves, such as those in Wave Test 1, that would otherwise displace the robot several centimeters. With Wave Test 1, Dactyl 8 had no measurable displacement due to the waves generated, Fig. E4. The original capped foot had the most displacement, followed by the flat foot. We believe that this is due to the larger cross-sectional area of the foot that prevents it from sinking into the sand. Interestingly the dactyl alone, without inward gripping was sufficient for this behavior.

Finding 4: In waves powerful enough to displace the robot even with dactyls (Wave Test 2), dactyls delay dislodgement and reduce total displacement after 10 waves. In Wave Test 2, we generated ten waves in order to force the robot to displace, Fig. E5. When using Dactyl 8, the total displacements are close to an order of magnitude less. When comparing the results for no grip and large grip, we found that there is a statistically significant difference in the amplitude (the total distance traveled forward and backward by the robot per wave) between both the original capped

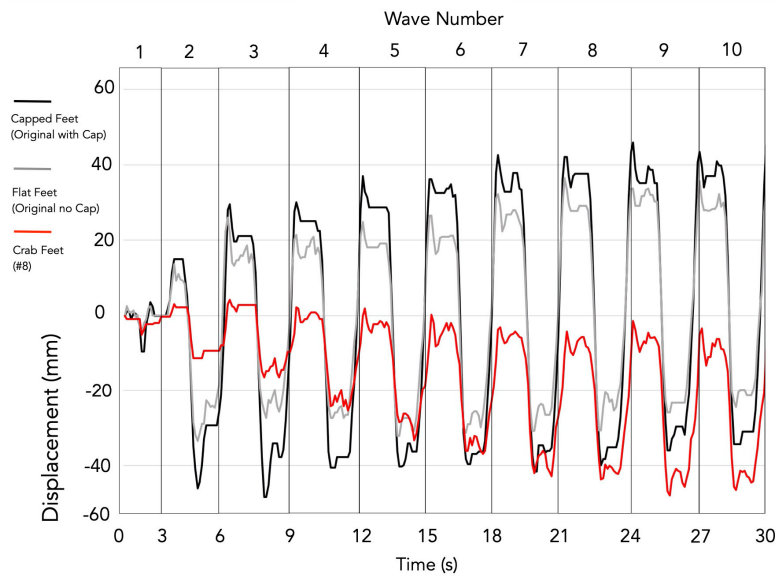


Fig. E5. The position of the robot in Wave Test 2 during 10 waves in the lab tank with a large grip. The displacement amplitudes are greatest with the original leg with the cap, are lessened with the original uncapped foot, and are the smallest with Dactyl 8. The displacements between each wave along with the total displacement from before the first wave to the end of the last wave also follow this trend. The displacements for all feet are in Appendix A.

and uncapped feet and Dactyl 8, where Dactyl 8 significantly minimized the amplitude of the displacements caused by the waves, Fig. E6.

Finding 5: Legs with crab-like dactyls can traverse a range of natural terrains such as gravel and sand (dry, wet, or submerged) in lab tests. In lab tests, dactyls can be used for a range of walking speeds on gravel and sand. The speeds with the dactyl are slower (30% to 70% of the speed with the original feet, depending on surface), see Fig. E7. It may be that speeds can be improved with gait optimization in future, but likely some speed loss is unavoidable with inward gripping dactyls. However, on the natural terrains we tested, unlike on man-made surfaces (smooth, hard tile), dactyl slip does not prevent forward locomotion. Taken together, these findings show how optimal leg design for robots for surf zones will be divergent from typical land robots.

Finding 6: With crab-like legs, a robot can walk into waves that crash over the body of the robot. We tested our robots at freshwater beaches with sand and pebbles in windy September weather.

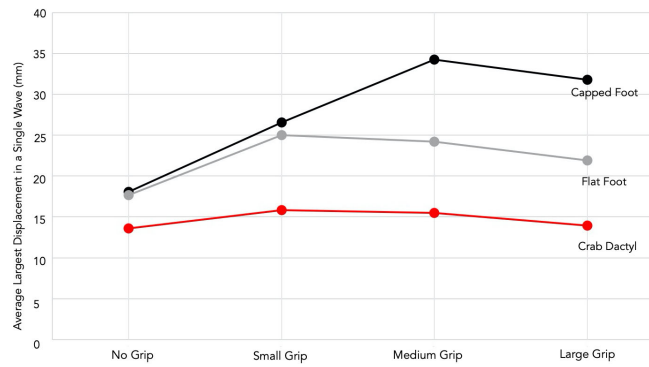


Fig. E6. The displacement per wave averaged over 30 waves (reset every 10 waves) for each grip and foot type, shows that crab-like dactyls decrease displacement even when waves dislodge robot.

The Hexy robot (the same one in tests above) was able to walk directly from dry ground into the water with slow alternating tripod gait. Natural waves are variable and for many waves the robot held on but some waves caused visible displacement of the robot, especially when the robot was deep enough to float. However, this can be addressed by reducing the buoyancy or adding weight. Specifically, the electronics compartment (including batteries and control board) is less than half the weight of the structural components (legs, actuators, support base) but more than half the volume. Reducing the volume of the electronics compartment by 45% would make the robot neutrally buoyant in freshwater without increasing weight.

Finding 7: Legged robots can walk completely submerged underwater on lake beds. On two calm summer days, we tested Klann mechanism robots in two freshwater lakes. Two robots with Klann mechanism legs were developed in parallel with the robots with articulated legs for comparison,

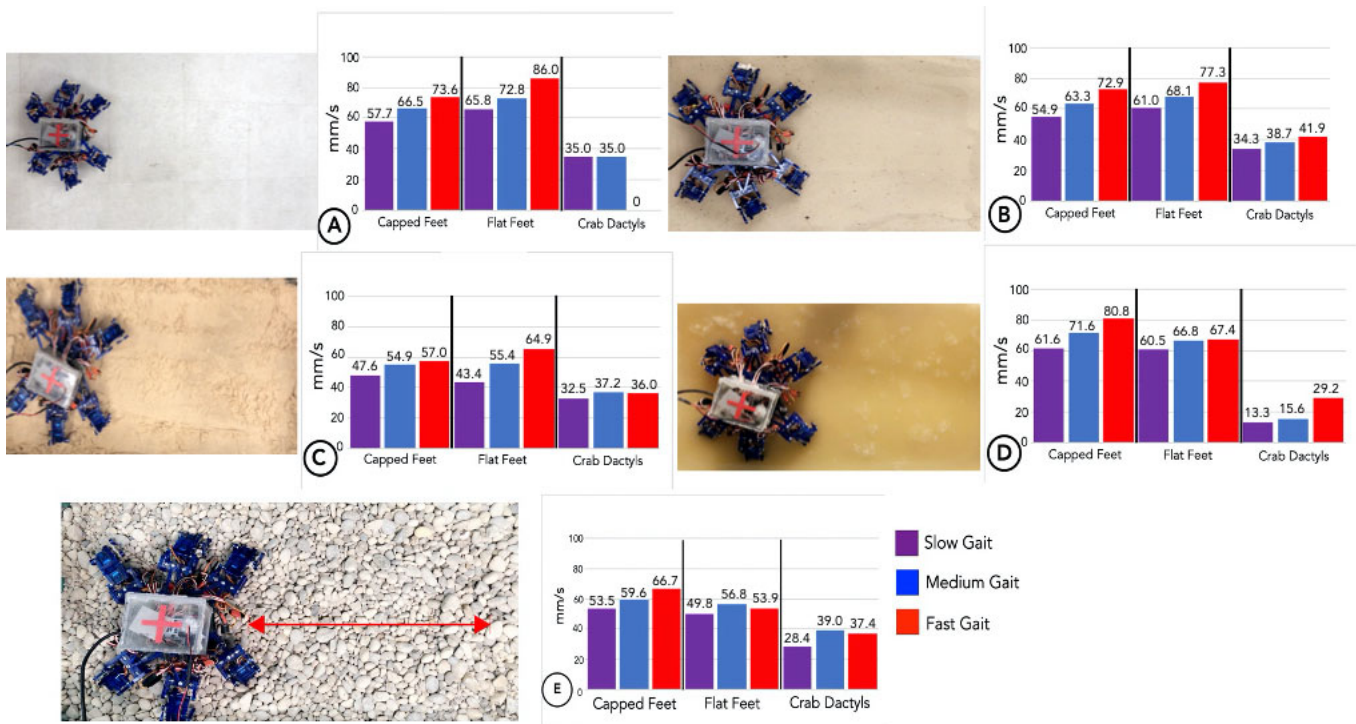


Fig. E7. The robot's speed was evaluated on several different substrates (n=15): hard smooth linoleum tile (A), dry sand (B) wet sand, (C) and submerged sand with 25.4mm of water above sand line which is enough to completely submerge feet of the robot (D), and rock bed (E).

and it turned out to be easier to fabricate this design with spring 2020 COVID19 precautions. Klann mechanism legs were able to walk from the wet sand at the edge of the beach into the water until depth was limited by remote control range. In one shallow inland lake, the robot went 30 feet until it reached a depth of 3 feet. In Lake Erie the depth increased faster, so it only went a few feet before reaching a similar depth, similar to lab tests. Each of these tests was performed with an added aluminum weight that increased dry mass by 30%. With this mass, the sinkage in fine dry sand was excessive. However, while basic rigid Klann mechanisms do not grasp ground, it may be possible to modify a simple leg mechanism to do so with a combination of passive compliance and offset gait control. These tests will help us refine robot design, including exploring potential simple mechanism legs that may be able to grasp the ground to resist waves.

Finding 8: Sensors can be added to dactyl feet to measure ground contact forces. At the dactyls, small magnets and magnetometers are an inexpensive and mechanically robust way of gathering data on six axis strains at the feet as they interact with terrain. As can be seen in preliminary data figures, such as Fig. E8, consistent spikes correspond with onset of stance and changes in load distribution. Such data has potential to inform stepping patterns or classify terrain. Other types of sensors that might interfere less with electromagnetic scans that are currently used for munitions response could also be explored.

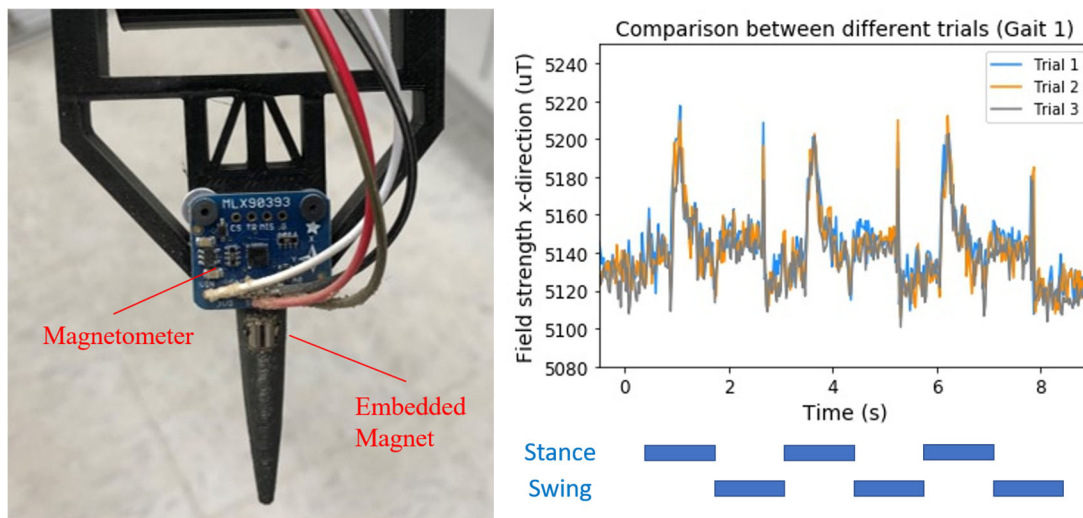


Fig. E8. Sensor embedded leg and data from leg on hard surface showing consistent peaks that correspond with stance.

This work shows that crab-like legs can be beneficial for surf zone robots to address the challenges of sandy terrain, wave disruptions and potential obstacles. When the feet penetrate deeper into the sand, extraction forces are increased and displacement due to waves are reduced. Preliminary versions of these results are interesting for mechanics of granular media, biology, and robotics (we have presented at conferences reflecting this [26], [28], including one conference where we were tied for 3rd place (<http://uasr.xjtu.edu.cn/info/1053/2033.htm>) and our results are in revision with Bioinspiration and Biomimetics (the best journal for specifically bio-inspired robotics, impact factor 3).

Implications for Future Research and Benefit

Proving this concept of “grasping the ground” was successful and will enable lighter amphibious robots. If pulling inward to engage feet increases the effective weight in very shallow water by one third, then the robot that pulls inward can be 75% of the weight of a similar robot that does not. When that lighter robot emerges from the water to walk on dry sand, it can do so more efficiently both because cost of transport typically scales with mass and also because it sinks into the sand less. Specifically, our test with Klann legs show that carrying an additional 30% weight makes it hard for the robot to walk in dry sand. Thus, since grasping reduces weight required, it could enable otherwise infeasible legged robots. Even small reduction in required weight reduces battery requirements, which would in turn increase mission length. Future robots could grasp the ground intermittently, perhaps using wave forces for locomotion, increasing efficiency even further.

We believe follow-on projects will enable a robot that can walk from dry sand into waves into greater than meter depth water. Using legs instead of tracks, fins, or wheels used by other amphibious robots [1]–[5], [25] could better enable traversal of rough, uneven terrain. The key will be reducing the volume the robot displaces in water so that the same weight of robot will have density equal to or greater than water. Specifically, as fabrication facilities reopen after the 2020 pandemic, robot components can be swapped from 3D printed parts to machined metal and plastic parts increasing density and strength. Additionally, machined tolerances will allow us to create more compact enclosures for electronic components. Another strategy can be adding more legs to decrease the ground pressure on sand (while six legs is the minimum for ground walking with stable tripods, crabs are decapods with ten legs which enables more distributed ground forces when needed).

For practical implementations, it will be critical to determine the simplest effective legs for anchoring. This project has identified several critical parameters (foot shape, foot trajectory, number of feet, body power-to-volume) that can be optimized. In future, our prototypes can be used to compare articulated legs with simpler wheel legs or reduced actuation mechanisms such as Klann mechanisms. We expect that augmenting these simple mechanisms with passive compliance and custom feet shapes will show increased grip forces which will ultimately enable better performance in waves and sand. If so, simpler legs can be easily added to other devices to create walking sensor beds, quadcopters that can walk or reposition after landing, diver-following tool chests, or modular swarms of amphibious robots.

A more in-depth analysis of requirements for grasping in response to waves would also be valuable in addressing unanswered questions such as: For trafficability and energy efficiency, when is it better to use small legs versus large wheels? Can mechanics models assess feasibility for particular mission lengths and conditions a priori? Can detailed mechanics models be used to determine best dactyl shapes to take advantage of particular environments? An additional benefit could be in understanding more about how biological crabs are likely to be affected by ecological changes.

Direct applications of this work can include novel mobile robots in two categories, Fig. E9. First, crab-like legged robots can be deployed on a tether from a surface boat to investigate or retrieve objects previously detected by towed or overhead surveys. Testing of a preliminary robot like this

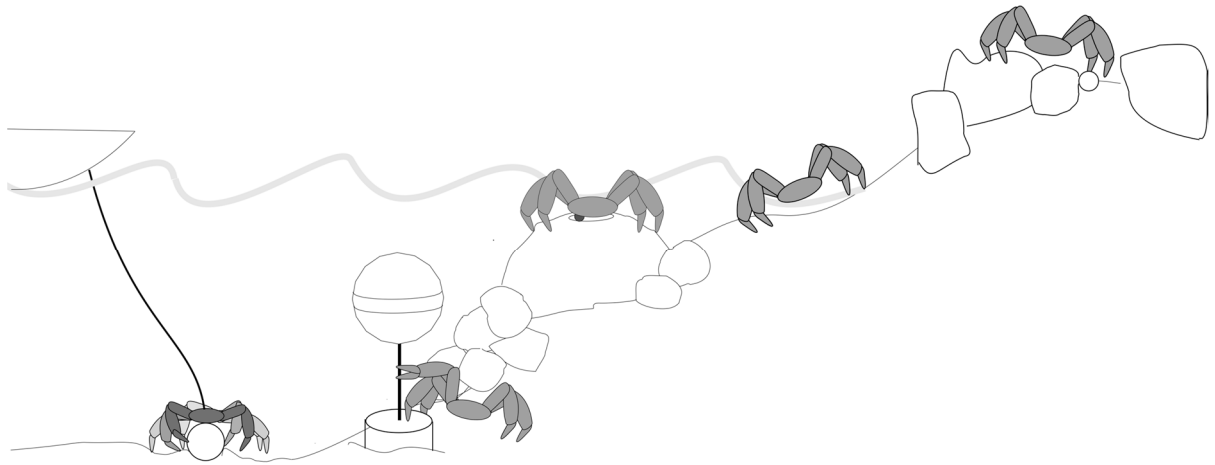


Fig. E9. Amphibious robot concepts that can be used to respond to munition. Such robots can be deployed from either a boat or from a beach.

would require developing additional data analysis for leg sensors, adding a reinforced tether, developing control for spiral searching maneuvers, and refinements of robotic legs to grasp and lift target objects. Second, this work could be applied to robots that need to travel along beaches, sandbars, and waterlines. Such robots could be integral to environmental clean-up because they are light enough to be deployed from the air and low enough to the ground to take surface samples, operate under docks, or even unbury partially covered munitions.

Final Report: SEED Crab-like legged robot for accessing and classifying munitions in surf zones

Objective

The goal of this SEED project is to evaluate the degree to which it is feasible for a robots' legs (e.g. Fig. 1) to anchor the body to the ground by grasping the terrain. Our hypothesis is that by selectively creating inward tangential forces between opposing legs, crabs grasp the ground for traction greater than their weight when needed to be able to anchor during waves, and release for efficient wave-riding and swimming. Is anchoring in wet sand compatible with walking on dry sand? What specific design components are essential? To answer this, we

1. Developed amphibious platform robots with several different leg and foot designs
2. Evaluated anchoring of robots in lab wave tank, which we build during this phase
3. Demonstrated legged walking on range of substrates, including freshwater beaches
4. Demonstrated embedded sensors in the legs, which may enable smarter gaits for heterogeneous terrain.

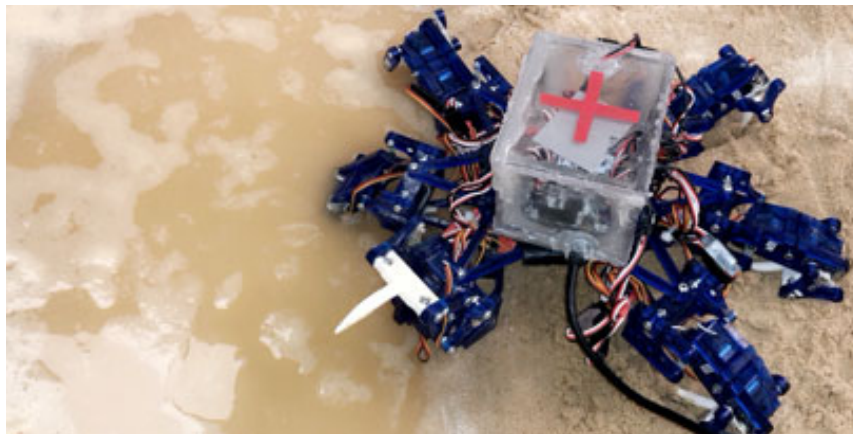


Fig. 1. Amphibious hexapod robot uses crab-like dactyls (white) to walk from dry sand to sand submerged in water.

Background

Munitions can land anywhere and may not be close to smooth paths. Amphibious mobile robots (Fig. 1) can be valuable tools for future munitions response, enabling remote surveys, retrieval, and disabling of potentially hazardous unexploded ordnance. In particular surf zones (areas of the ocean with shallow water) are critical, as described in the SERDP munitions response statement of need (MRSON-21-C1). Accessing unexploded ordnance in surf zones can limit their exposure to air, wave forces, land animals, and humans.

Background State of the Art Amphibious Robots

Amphibious vehicles often are designed based on land vehicles for rough terrain. Unmanned vehicles with wheels that are large relative to obstacles have been proposed. For example, ARGO J8 Atlas [2] is the size of a small car, floats on water to swim, and drives over fallen tree trunks with its eight-wheeled suspension system. Using tracks between wheels distributes the weight across a greater area for traversing sand, as in SeaOtter [5] which can tow scanning equipment [MR- 201712].

Understanding how to help smaller robots traverse surf zones may decrease risk of accidental detonation of UXOs and will reduce equipment loss cost, environmental damage, and hazard if detonated. Animals are adept at crossing natural terrain and provide inspiration for robot designs. For example, the same flexible spine motion that results in swimming in water [29] can also be used to crawl or supplement legs on the ground, as in the robotic salamander Pleurobot [30], [31] or in swimming/wheel-leg hybrids [32]. We have developed worm robots that crawl on sand [33]. Other robots use screw-motion which simulates worm-like locomotion [34][MR-2325]. The final report on [MR-2325] recommends avoiding above-ground silt and sand or very shallow water which can “beach” the robot.

Legged robots offer a reasonable trade-off of speed and traversability for unmanned hazardous environment access. Legs can be fast over rough terrain because they can walk over obstacles, can move the robot sideways as well as forward, and can also act as paddles for swimming in water. Amphibious Whegs’ spokes terminate in arced feet that together approximate a wheel, but can step over obstacles [3], [35]. Aqua hexapod robots [36]–[38] have had walking legs, flipper-like legs, and a hybrid design with a circular wheel cage that encloses and protects the flippers [39]. The compliance of these legs can be designed for efficient running or swimming. Biologically-inspired leg designs with more degrees of freedom, for example inspired by crabs [19] and turtles [4], have demonstrated amphibious locomotion, but are typically rigid and thus need precise control for challenging terrain. Robots with soft legs are showing increasing promise over terrain [40].

Sand, rocks, and unpredictable water currents are still major challenges for robots. For example, on sand, robots can become entrapped as wheels dig themselves deeper. Rocks can block or trap legs. Waves can overturn robots. In order to support forces tangential to the ground, the end effectors are more useful when internally reinforced for shear. Here we propose that shear forces can be important not only for traction, but for additional stability in soft terrain. If we could mimic the way crabs exploit these features for digging and walking, it would completely change the reachable map for unmanned survey and munitions recovery.

Background Crab Biology

Crabs’ characteristic shapes with wide bodies, strong walking legs and tapered feet seem to have evolved several times from different invertebrates, a process called carcinisation [24]. Without a

tail for swimming, the anatomy is specialized for navigating strong currents and squeezing into tight hiding places – both on land and in water [41].

Underwater, crabs walk with a wider stance and “punting” gait in which the animal alternates between pushing against the ground and gliding through the water, which is distinct from the regular tripod or wave gait the same species uses on dry land [42]. It would be easy to dismiss this punting behavior as a simple low-weight adaptation to sprawled-posture running (implemented to prevent overturning in cockroach-inspired robots [43], [44]). However, in the wild, fast escape runs are often brief [45], while hydrodynamic destabilization forces are continual and can be larger than the body weight [12].

Thus, our hypothesis is that robotic crab-like walking depends on more than just a low center of gravity, but also on using the legs to grasp the ground. This is supported by biological observations of crabs’ gripping and digging behaviors [20], [46]. The design implication is that a crab-like robot should be designed not only as a walking robot, but also as an inverted grasper. As a result, rather than fighting waves to survey a surf-zone, the future robots could use favorable tides and waves to traverse a beach with low power. By timing a “punt” with a desirable current direction of the waves lapping the shore, the animal might be able to efficiently migrate over long distances and scale obstacles that are much larger than its smallest body height. Although, single-leg punting gaits have been shown to be stable over uneven terrain in still water [47], our grasping gaits will be novel for crab-like robots, and combined with environmental characterization, could be transformative for accessing, classifying, and remediating munitions sites.

Background Crab Robots

Arthropod legged walking has provided inspiration for robotic walking in several key areas. Underwater walking with Ayers’ eight-legged lobster robot [11], [48] and simulations [49] identifies two challenges: crossing uneven rocky sea floors, and getting traction because buoyancy decreases effective weight. Proposed solutions are, respectively, omnidirectional locomotion with legs and hydrodynamic control surfaces analogous to lobster’s tails and pinchers [11]. Here we propose that using leg strength to grasp the substrate will reduce the need for a tail and designing planar legs for diverse terrain will improve performance while still retaining omnidirectional motion options in extended projects.

At large scale, Korea’s amphibious Crabster, which is taller than a person, is designed with strong enough legs to walk on dry land or explore reefs while disturbing less silt than using propellers [18]. (Distributing silt increases turbidity which makes it hard to classify potential UXO (unexploded ordnance) from surrounding debris). However, such large prototypes are costly, especially for design iteration. Here, because the preliminary robot will be roughly the same scale as a large crab, design-fabrication-test cycles will be faster and the robot will be useful in a different niche of environmental missions (unmanned, fast fabrication, deployable from other unmanned vehicles, and low-cost redundancy).

The simpler the design the better because increasing the number of actuators decreases the power to weight ratio. Thus, actuating individual joints requires a trade-off between joints that are fragile or robots that are heavy. On one end of that spectrum, Robugtix makes a table-top spider robot capable of smooth life-like motions [50]. However, even enthusiastic positive reviewer’s (such as MythBuster’s Adam Savage), find that the joints can break just turning the power on. This makes it unlikely that the robot would work well autonomously crossing fields of debris or in surf zones. We consider both reduced actuation and stronger motors as possible solutions to this problem

Finding ways to achieve sufficient locomotion without actuating each joint may be the key to lightweight, low cost, high performing amphibious robots. In the 90s, Ariel reduced the 9 degrees of freedom (DOF) of a crab leg to 2 DOF per robot leg [19], [20]. Like its predecessor Ursula from the same group, Ariel was tested in lake beds where sea mines detection was characterized with various sensors (ultrasonics, acoustics, metal-detection) [19], [51]. Ariel's primary design improvements over Ursula was in (1) more crab-like sideways walking legs, (2) variable stance width from legs and (3) reversible joints that permitted the legs to work upside down if overturned. Here, the proposed designs will benefit from modern actuators, fabrication with rapid prototyping, and simple controller programming (in this project) which can lead to more complex smart control (a project funded by ONR).

With a single source of continuous rotation (one degree of freedom), the complex multi-jointed legs of crabs have been approximated with Klann [52] and Jansen [53] mechanisms, six- and eight-bar linkages that provide low-center of gravity legged motion. Both of these linkages have been implemented on robots [53]–[56], but except for a graphical simulation [57] the behaviors seem limited to smooth surfaces. A key disadvantage of prior implementations is that the distance between the stance feet is typically rigidly fixed. As a result, the feet do not conform to the terrain. Here, we begin to explore mechanical compliance and adaptive synchronization for a grasping gait using reduced-actuation mechanisms.

Our goal is to determine how effective a naïve tactile or even passive search gait will be for finding footholds in wet and dry surf zone terrains. In dry environments, spider-like robots modify alternating tripod gaits based on mapped obstacle fields [58] or have responsive gaits for climbing 20° inclines with sensor-responsive gaits that may apply in future to cobblestone streets [59], [60]. Biologically-inspired control solutions from arthropod neuromechanics models show that simple animals achieve adaptive behavior from a combination of compliant mechanics and adaptive control, which applies to robots including in our research group legged robots inspired by cockroaches, mantises, and dogs [61]–[63].

Background. Tactile Sensing

Detecting ground reaction forces is critical for both locomotion and classification of terrain and embedded munitions. In our current work, we are demonstrating the value of sensing ground contact for worm-like locomotion [64]–[66]. We find that sensed actuation load can be used to estimate contact forces but that contact sensors are even more reliable. Recent developments in sensors are making it possible to add sensors in new places. For example, sensors can be embedded in grasper fingertips [67], [68], can be integrated with actuation [69], or can use soft materials as dielectrics [70]. Sensors and legs can be fabricated together out of foldable layers [71]. Power can be routed through continuously rotating bearings to taxels (tactile pixels) on C-shaped legs to determine ground stiffness and friction [72].

We envision tactile sensing as close-range supplement to longer range information from acoustic [MR-201714][MR18-1443] and LIDAR scanning [MR18-1459] as well as improve autonomous locomotion. Force/torque sensors at the tip of a spider-like legs can differentiate twelve different ground types [73]. We have used Markov modeling where the sensor values must be interpreted in the context of stroke phase [65]. Other machine learning techniques, such as Support Vector Machines (SVMs) can be used for well-defined categories [72]. Since this project focuses on design, gathering data from leg-embedded sensors for underwater traversal of simulated munitions will help to establish the required sensors for classifying and extracting partially buried UXO.

Goal – grasping the ground while still being able to execute walking gait

We propose to build on techniques studied in climbing robots to improve ways crab-like robots grasp the ground in order to improve the stability under hydrodynamic forces. “Grasping the ground” to anchor is a whole-body challenge. Typically, grasping refers to a large robot picking up a smaller object with an end effector that provides “force closure” – such that the friction cones at contact points resist any reasonable disturbance forces. Here, to grasp the environment as part of a steady walking gait, the concept is to use ground friction and compliant feet to apply large equal and opposite lateral forces at the legs to anchor the body at every step. For smooth cylindrical UXO embedded in the terrain, the included leg angle and friction will determine whether inward forces can resist outward normal forces. (E.g. for angle 90° , minimum coefficient of friction would be 1). Larger robots (relative to cylinder radius) require less friction. However, even if the robot is smaller, it may be able to take advantage of non-convexities (roughness) in terrain to support even larger lateral forces, especially with animal-inspired bristles, claws, and spine to take advantage of non-Coulomb friction. In this way, using the concept I named “Distributed Inward Gripping” (DIG, Fig. 2), insects and our climbing robots can climb steep surfaces and even inverted on ceilings. Here, we determine the extent to which DIG can be applied to crab-like dactyls to help maneuver in granular media.

In a normal walking gait two phases (swing and stance) are considered, but to anchor requires a third phase (a searching motion at the beginning of stance). Searching for the grasp contact requires coordination. Between swing and stance, the legs must be pulled inward, compressing compliant structural elements to maintain contact and build shear forces. On substrates that are essentially flat but with small roughness disparities or holes for grasping, the search can be horizontal (parallel to the substrate) and use passive compliance to stop when a suitable hold is found. However, the larger the search, and the greater the compliant displacement, the smaller the step. In the proposed work, the search path will be fixed by the mechanism design and active phase responses will be developed. In extension projects, the robot will be able to increase step height for larger obstacles and more complete 3D searches.

Finally, amphibious terrain is notorious for “sticky” terrain, especially where water sources can bubble up from below, and the robot needs to be able to retract feet to prevent getting stuck. A complete survey of all terrain types is outside of the scope of this SEED report, but it may be advantages to modify feet to prevent excessive sinkage with crab-like bristles, ski-pole like expanders may be important. A tapered dactyl will pull out easily along its length but support large forces in shear. Smooth hard dorsal surfaces will have low friction in unloaded state but could support soft interior grasping surfaces. In the robots developed in extension projects, redundant legs can be used to extract legs and carry payload. In field work, mission-specific legs and dactyls could be added to the platform, similar to the way biological crabs have specialized legs for pinching and swimming.

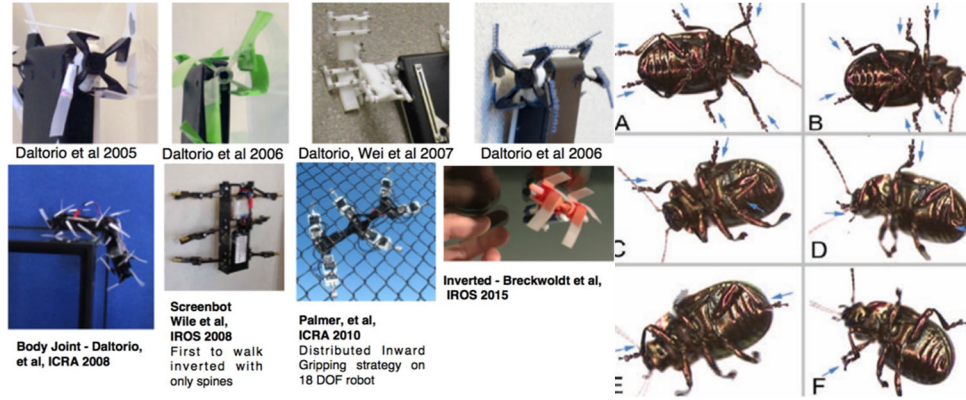


Fig. 2. Our climbing robots grip substrates with many different substrate/mechanism combinations, including the first to use micro-structured adhesive feet for climbing vertically and then later inverted, first to demonstrate exterior transitions with adhesive feet, and first to climb inverted using spines on a 1DOF robot [56], a concept which was later demonstrated with an 18 DOF robot [57]. Distributed inward gripping was developed based on observations of beetles arranging feet (blue arrows) to generate opposing forces [56].

Materials and Methods

1. Robot Design

The biological inspiration for our work is crabs, which can traverse sandy, rocky and wave-swept wet and dry terrain that current robots cannot cross with their many degree of freedom (DOF) legs. Like crabs, an articulated robot can independently control each joint. For expediency, the first articulated robot platform was based on waterproofing a commercial-off-the-shelf metal gear “Hexy” robot from Arcbotics. Subsequently, we built a second articulated platform with actuators with higher torque to weight ratio, referred to as “Sebastian”. These robots have 6 legs each (two stable tripods) but the legs could be duplicated to more closely mimic the 10 legs of crabs.

These robots are controlled to walk with alternating tripod gaits, in which at least three feet are always on the ground (aka in stance) while the other three feet swing to their next position. This is a typical gait used by many hexapod animals and robots. The novelty in this project is that typically the stance feet are stationary with respect to each other, whereas here at the beginning of stance the feet are pulled inward to develop forces tangent to the substrate. Thus, a small fraction (similar to a coulomb friction coefficient) of those tangential forces is available to resist disruptive forces normal to the substrate.

A critical element of the robot design is the shape of the feet. In crabs, the most distal segment of the leg is called the dactyl and it has a characteristic pointed shape. Typically, robots for walking on smooth hard surfaces have rounded feet so that they can contact the ground at one angle and roll to another angle. We 3D printed several foot shapes and tested them on the Hexy robot. For walking, the dactyls have to be proportionally sized. To engage with the sand, the best feet were curved with tapering circular cross sections, similar to crab dactyls.

Additionally, because actuators can become a point of failure or interfere with electromagnetic sensing, we have built legged platforms with reduced actuated Klann mechanism legs. Klann mechanisms are a linkage that transforms rotational motion from a single drive servomotor into elongated steps while keeping the center of mass of the robot low to the ground. In this way, one central servomotor can control a number of legs from a protected chassis.

Table 1. COMPARISONS OF THE DIFFERENT ROBOTS UTILIZED

Robot	Weight	Walking Height	Step Size	Number of Legs	DOF Per Leg	Total DOF	Actuator and Torque
Hexy	1.3 kg	18 cm	7 cm	6	3	18	0.245 Nm
Sebastian	2.96 kg	21.6 cm	2 cm	6	3	18	Savox (SV1270T)G 3.43 Nm
Klann 1	0.92 kg	17.3 cm	7.5 cm	4	1	4	Dynamixel (MX-64) 5.5 Nm
Klann 2	3.21 kg	13.5 cm	6.2 cm	8	1	2*	Stepperonline (17HS15-1504S-X) 10.45 Nm (Gearbox ratio 11:1)

*Klann robots can control more than one leg with the same servo

We tested four different robots, compared in (Table 1.) Each robot platform has a particular testing goal. Hexy is simple and fastest to develop and test. Sebastian we developed to add sensors to the feet and increase torque and robustness of articulated joints. It has many more control options, that haven't been fully explored yet, but it is currently taking small steps to probe the ground. Klann 1 is for testing compliance in the joint mechanisms in the lab and Klann 2 is a more rugged a platform for testing additional simple leg mechanisms in beaches.

Sebastian Robot: With the baseline results from the commercially available Hexy robot, a more durable crab-like robot is needed to better maneuver the complex environments, Fig. 3. This new robot has more robust servomotors than the Hexy model, permitting the robot to operate for longer periods of time and have less servomotors break from the stresses of the environment. The Sebastian robot was designed to have its femur and tibia be 1.5 the length (Fig. 3A) of the coxa to maneuver over a wide range of obstacles. This aligns with crab measurements provided by Dr. Jennifer Taylor at Scripps Institute of Oceanography. The specifications of the main structure are given in Table 2.

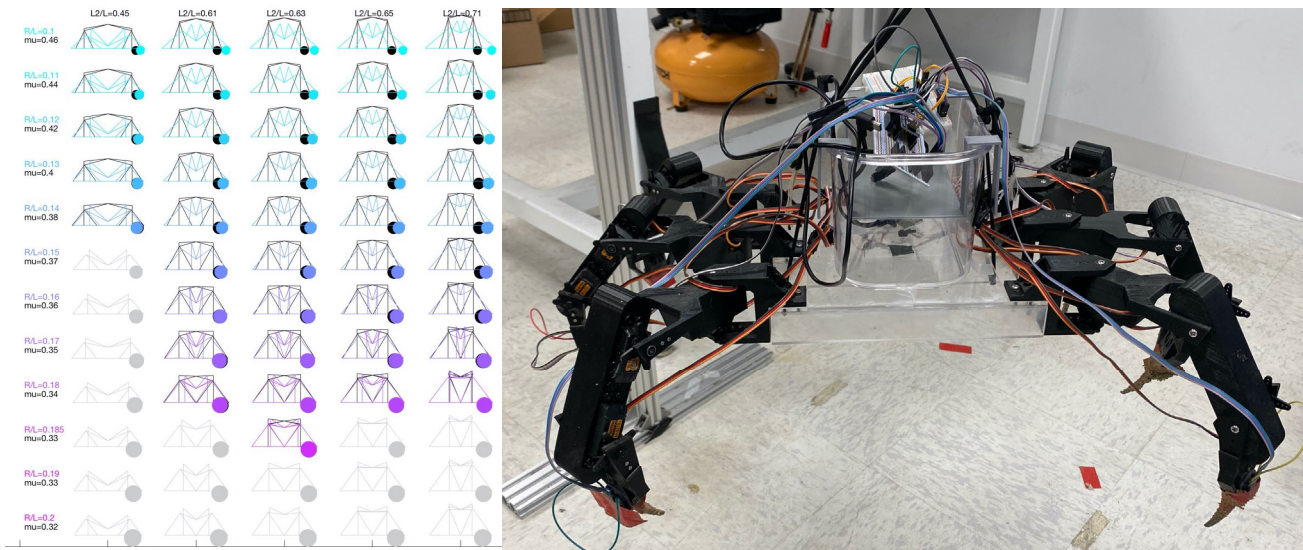


Fig. 3. A. Clearance range of crab-like robots over obstacles of varying diameter. The ratio of 1:1.5 for the femur compared to the tibia and dactyl allowed the robot to navigate over the widest range of obstacles. B. The assembled Sebastian robot. Each leg was made of PLA by a 3D printer and was equipped with three servos (Savox SV1270TG) to provide high torque (486.1 oz-in, 3.43Nm). Mass of servo is 56 g. Compared to the Hexy robot (torque per mass is 0.0223Nm/g), Savox SV1270TG has 0.061Nm/g

Table 2.

SPECIFICATIONS OF THE SEBASTIAN ROBOT

Specifications	Values	Specifications	Values
Sebastian Crab		Savox SV1270TG	
Coxa	90 mm	Running Current (No load)	6V-120mA, 7.4V-150mA
Femur	75 mm	Stall Current (At locked)	6V-5500mA, 7.4V-6800mA
Tibia	120 mm	Idle Current	4.8V-5mA, 6V-5mA
		Torque	6V-361.1oz-in, 7.4V-486.1oz-in

Klann 1: Klann 1, Fig. 4, was built to understand how compliance affects the maneuverability of Klann robots in complex environments. A Klann robot consists of seven linkages that, when rotated by an actuator, allow the foot to follow a smooth cycle with a flattened part during stance (Fig 7A). Klann 1 consists of the main body and four legs, which are driven by four smart actuators to maintain a 180° phase difference between the diagonal legs to allow them to move together (Fig 7B). Two springs and one slot are attached to the link L4 which are used as compliance. Based on prior work in climbing robots[74], we hypothesized that compliance in the tangential direction will enable the robot to passively search for footholds, loading the spring as tangential forces are

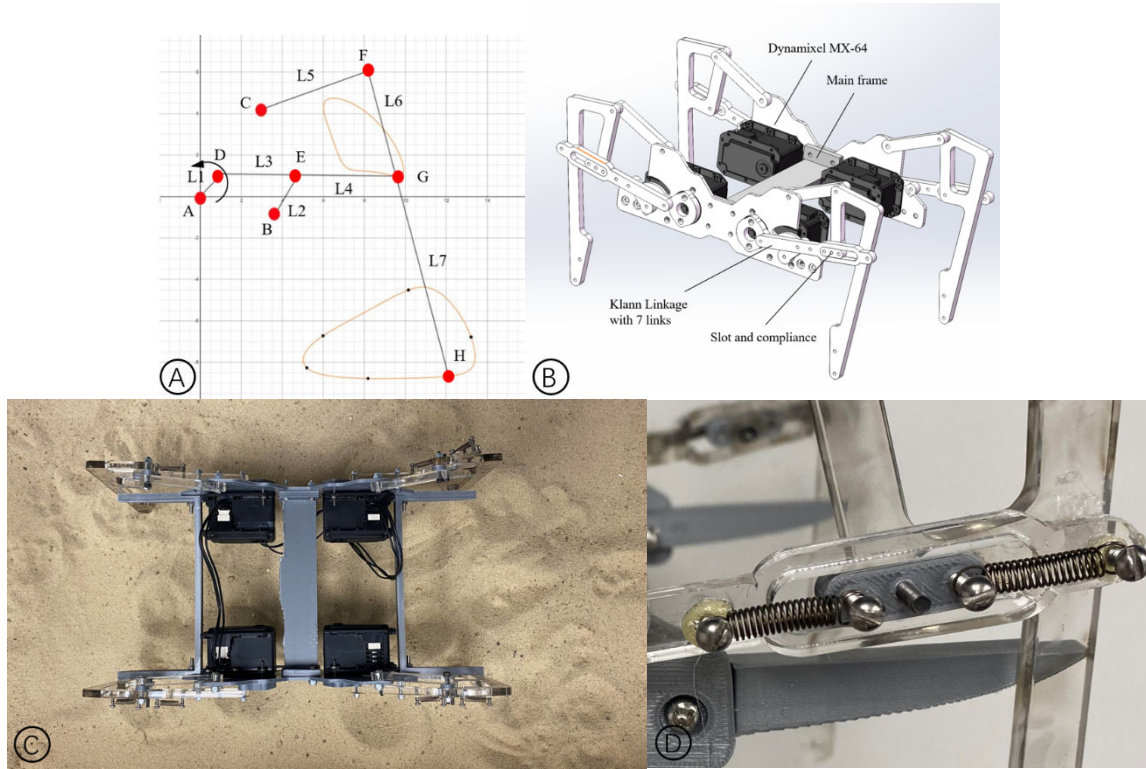


Fig. 4. A The path of each joint of the 7 bar linkage that makes up each leg of the Klann 1 robot. (Position A is (0,0), position B is (36,-9), position C is (30,42)) B. The modeled version of the Klann 1 robot C. The main frame of Klann 1 is 3D printed (PLA). Legs are acrylic boards ($\frac{1}{4}$ inch) cut by laser cutter (Epilog Fusion Pro 48). D. Compliance of the Klann 1 that consists of one slot and two springs (225.9N/m).

applied. Additionally, this could provide greater range of motion for overcoming obstacles. The path of the robot's legs is shown in Figure 4A, the model is shown in Fig. 4B. The specifications of the robot are given in Table 3. To determine the trajectory of the Klann linkage, we utilized Rojas' method [75].

Table 3.

SPECIFICATIONS OF KLANN 1

Specifications	Values	Specifications	Values
Klann 1		Lengths of the links	
Length	270 mm	L_1	15.0 mm
Width	174 mm	L_2	22.5 mm
Height	165 mm	L_3	37.5 mm
Mass	2.5 kg	L_4	34.5-49.5 mm
Number of feet	4	L_5	55.0 mm
Number of MX-64	4	L_6	52.5 mm
Torque of MX-64	5.5 N.m	L_7	110.0 mm
Spring Stiffness	225.9N/m		

Klann 2: Klann 2, Fig. 5, was built to understand how well a Klann robot can maneuver in complex environments such as seabeds. The seabed is especially challenging due to the forces imparted by large waves, seeking to displace the robot. Klann 2 consists of two motors (Stepperonline 17HS15-1504S-X1) and eight legs to create a more stable and reliable robot for navigating this terrain. Each motor controls four of the legs to maintain a phase of 180° . Dimensions are specified in Table 4.

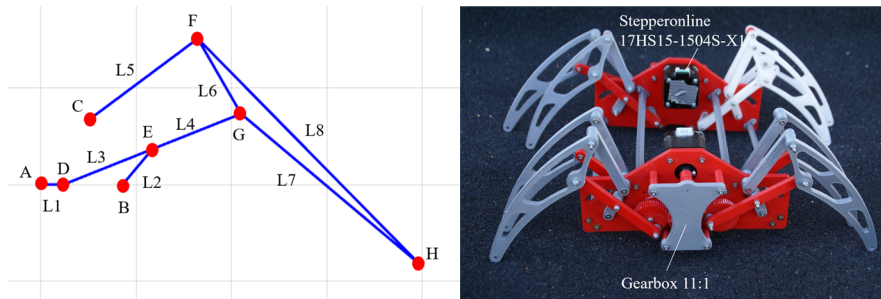


Fig. 5. A The path of each joint of the 7 bar linkage that makes up each leg of the Klann 2 robot. (Position A is (0,0), position B is (43,0), position C is (26,34)) B. The assembled version of the Klann 2 robot.

Table 4.

SPECIFICATIONS OF KLANN 2

Specifications	Values	Specifications	Values
Klann 2		Lengths of the links	
Length	270 mm	L_1	12.0 mm
Width	174 mm	L_2	24.0 mm
Height	165 mm	L_3	50.0 mm
Mass	2.5 kg	L_4	50.0 mm
Number of Feet	8	L_5	70.0 mm
Number of Stepper Motors	2	L_6	45.0 mm
Torque of Stepper Motors	0.45 Nm	L_7	121.0 mm
Gearbox ratio	11:1	L_8	164.0 mm

2. Dactyl Design

To demonstrate the relative contribution of the crab-like dactyls and inward gripping on sand, we chose to modify the metal gear HEXY robot kit from ArcBotics (Fig. 7A), a hexapod with three DOF) per leg. Specifically, the original “feet” are cut from blue acrylic and come with a rubber cap. The provided cap enlarges the contact area and friction between the foot and surface it is walking on, permitting the robot to navigate easier on smooth, hard ground. The final robot has a weight of 1.2kg.

The HEXY robot came with 6.35mm thick acrylic feet that forms a circular foot with a diameter of 7.9 mm. To evaluate how the robot would grip with different feet, nine different designs were created and tested, shown in Fig. 6.

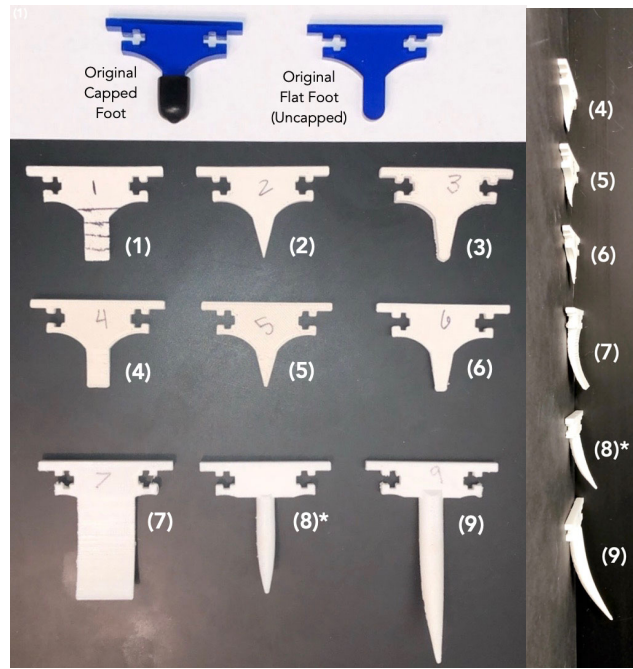


Fig. 6. In preliminary evaluations, we compared 11 different robot feet. We chose the crab-inspired foot 8, which will be referred to as Dactyl 8, due to its promising performance in both maneuverability of the robot and the ability to grip. Throughout this paper, we compare the effectiveness of the original capped foot, the flat foot, and Dactyl 8. See [26] for more detail on the dactyl design.

3. Robot Waterproofing

The servos were treated with multiple layers of modified silicone conformal coating (MG Chemicals) to make the servos watertight. After the solution dried, the servo output shafts were treated with Lucas Hi-Performance Multi-Purpose Marine Grease. This pairing protects the interior of the servo from any water entering the casing.

The electronics were mounted in a waterproof acrylic box that was modified by drilling holes on the sides to fit the wires that control each leg. The acrylic sides and holes for wires were sealed with hot glue and caulk, allowing the internal board to be waterproofed while maintaining control of the servos. The waterproofed robot (Fig. 7B) was powered off board with a TEKPOWER DC Regulated Power Supply (TP3005T) at 6V.

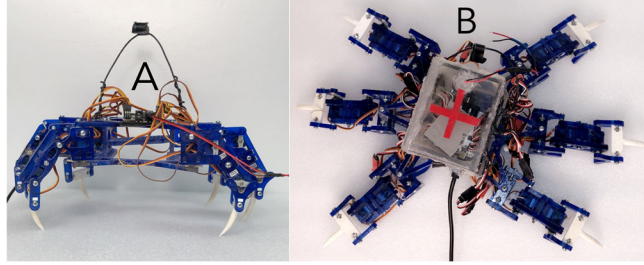


Fig. 7. (A) Hexapod robot before waterproofing shows white dactyls, blue HEXY legs, orange wires that connect joint actuators, and grip test harness (black loop) (B) Amphibious robot has waterproof electronics box (clear), and silicone and marine grease coatings.

4. Evaluation in lab wave tank

We built a plexiglass tank and filled it with Pavestone Natural Play Sand. The tank is waterproof so that we can evaluate dry sand, wet sand, and sand submerged in water. Between every test, initial sand conditions were restored by flattening the sand.

Vertical Grip Force Test: The robot was placed in the sand, then moved feet into either reset (no grip) or small, medium, or large grip stance. The distances between the dactyl tips in each grip are shown in Fig. 8.

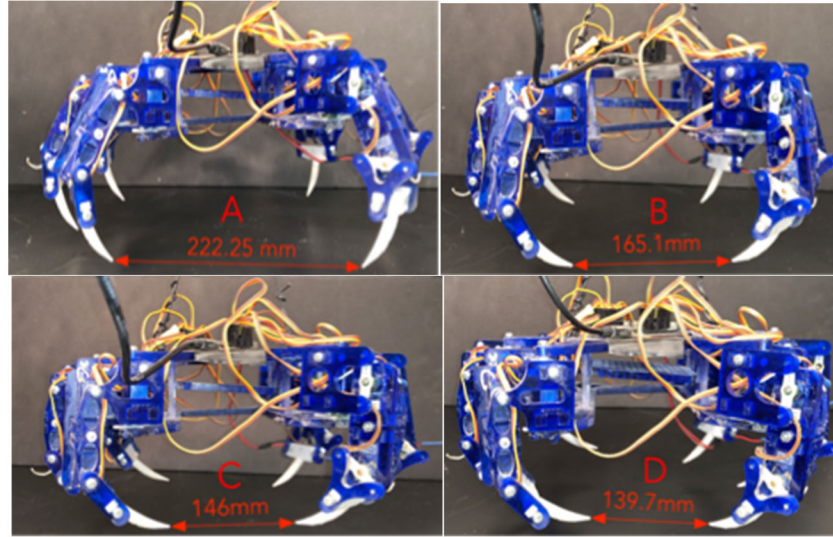


Fig. 8. The grip motions are shown here in air without sand for visibility. At the onset of stance (A) the distance between contralateral pairs of legs is approximately 20 cm. Gripping motions result in the distance being reduced to 74% for the small grip (B), 66% for the medium grip (C), and 63% for the large grip (D) with corresponding changes in dactyl angle.

Then a constant velocity ATV Utility Winch from Badland Winches (powered by an eTopxizu power supply (12V 30A)) pulled the robot vertically up with a digital force gauge (Nextech DFS50 Digital Force Gauge, published resolution ± 2.0 grams force) until it yielded from the granular media. The force gauge recorded the load for every grip test (Fig. 9). The maximum value shows

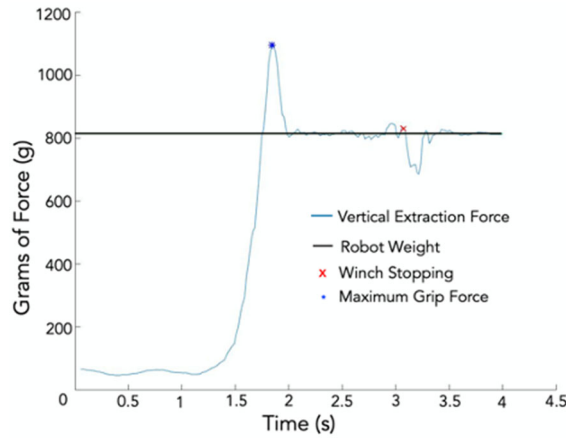


Fig. 9. The grip tests were conducted 30 times in each sand with each foot type while the robot performed one of the four grips of interest. The results are recorded as maximum forces as percentages of the robot's weight.

when the sand yields. Note that in some cases a second peak is visible when the winch stops, causing the robot to bounce. These secondary peaks are ignored. During the course of this project, we have increasingly automated the test set up to speed data collection with python scripts.

Klann I Grip Test: To determine whether compliance helped in gripping, the Grip Test was performed on the Klann I robot. We rotated each leg on the robot at the same speed to the smallest grip position and fully stretched the compliant springs so the compliance would have maximum effect on the system (Fig. 10).

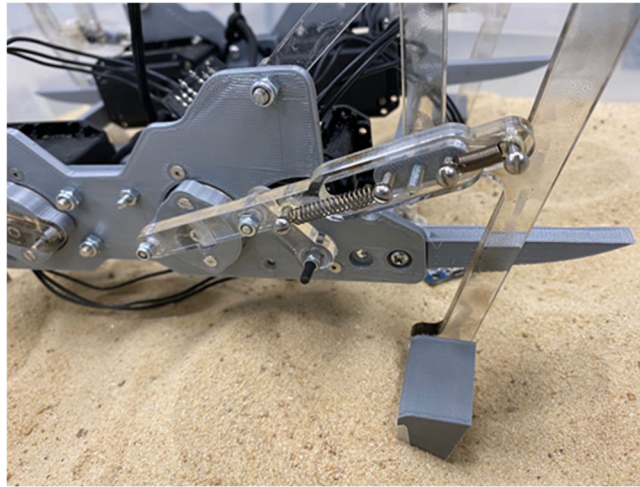


Fig. 10. The grip test setup for the Klann I robot. Here, the compliance in the spring is fully stretched in order to have the maximum effect on the grip.

Wave Testing: Waves were generated in the tank with a compressed air piston (CHLED piston SC63X200 controlled with an Arduino) attached to a flat partially submerged surface. The piston was powered by a (Bostitch 150 psi) air compressor that was set to 100 psi. The robot was placed on the sand in the water. For different configurations, the same number of waves were applied to the robot. In the first test (Fig. 11), the set position of the piston was manually supported and only

the total displacement of the robot was measured. These waves were sized such that with dactyls, no displacement occurred.

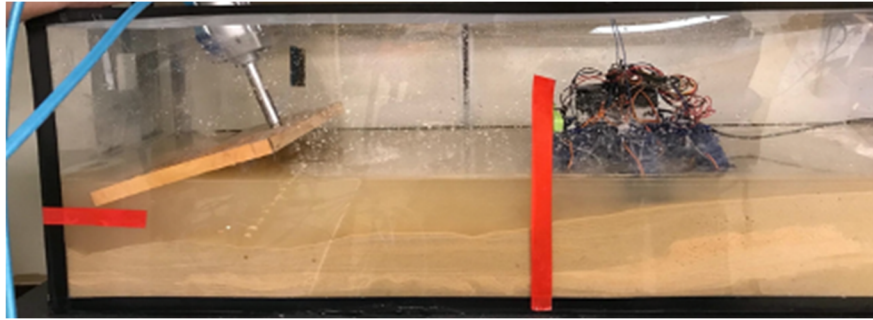


Fig. 11. At the red line, the water is 76.2mm deep. This water level reaches the bottom of the waterproof box on the robot. The water is 155.6mm deep where the piston is. The piston's initial depth is 25.4mm at 20°. The waves are 63.5mm at the red line and are generated 298.5mm away from the front feet of the robot. The board connected to the piston that is used to generate the waves is 228.6mm x 301.6mm. The stroke of the piston is 152.4mm. The piston was powered with an air tank at 100 psi. The waves were then generated at 3.2 Hz for four waves. After that, the robot's total absolute displacement was recorded.

In the second test, the piston was supported by a bracket. The robot was placed in the middle of the tank, then a metal rod was inserted through a hole in the placement marker (Fig. 12). This lined up the hole in the placement marker with the center-point of the 'X' on the back of the modified HEXY robot. The robot then moved into one of the three grip positions or, for no grip control data, the robot remained stationary. Waves were generated with a period of 3.133 seconds. This period was selected by generating one wave and tracking the time that it took the crest of that wave to travel down the tank forward, backward, and forward to the center point of the plate of the wave generator. This ensures that at any given point, there will only be one wave in the tank. This permits us to run the test for multiple waves and then split the video to produce multiple trials. After the robot was commanded to perform a grip, 10 waves were generated, displacing the robot. The displacement was tracked with open source vision tracking software Tracker [<https://physlets.org/tracker/>].

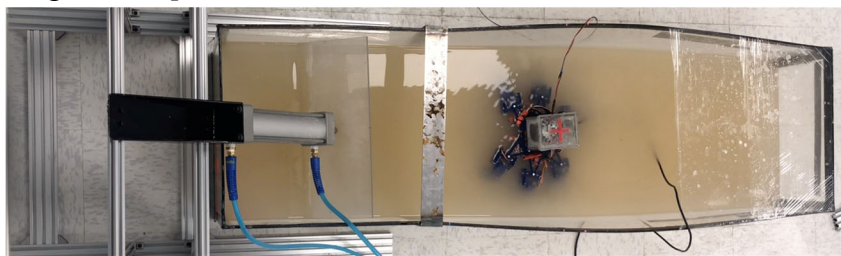


Fig. 12. Wave tank provides consist size waves to demonstrate effectiveness of dactyls to resist displacement.

To better prepare for testing in seabeds, a wave tank was constructed to better control parameters that we are most interested in, such as the wave size, depth of the robot, incline of the sand, and sand properties (Fig. 13). The wave tank is made with acrylic boards and sealed with polyester laminating resin and fiberglass. The wave generator was permanently fixed inside the tank in order to create the largest waves possible. It is set on an adjustable frame so we can change the angle of attack for the wave generator, which will alter the size of the waves generated.

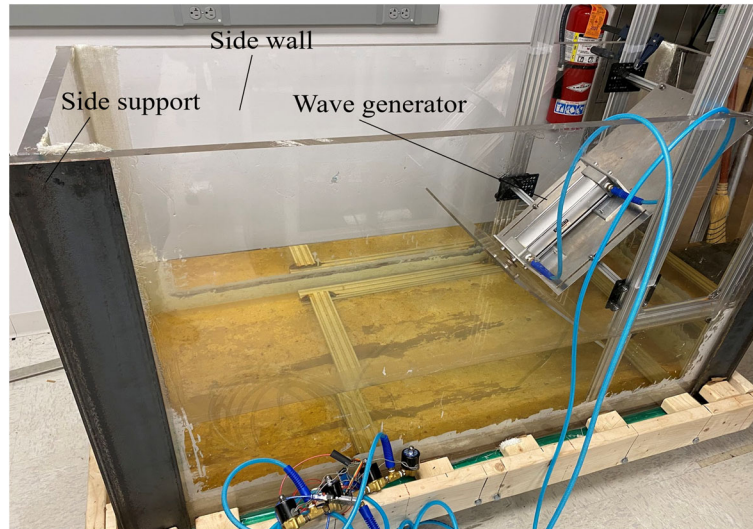


Fig. 13. Constructed wave tank for in lab testing to better control variables that could alter the results of our testing. This tank was made with 1 inch acrylic to combat the forces from the sand and water, and is 60 in long by 24 in wide by 36 in tall. The frequency of the wave generator for this tank is 0.27 Hz.

5. Leg-Embedded sensors

Small magnets and associated hall effect sensors were embedded in the legs to collect data while the robot maneuvers in different environments. The magnitudes of the X, Y, and Z magnetic fields act as an analogue for the component forces along the length of the dactyl. The small internal magnet acts as a node that could be sensed by the magnetometer and reveal small translations between the dactyl base and tip of the dactyl. The corresponding changes in magnetic field strength and direction can be mapped to component forces when interpreted by an Arduino.

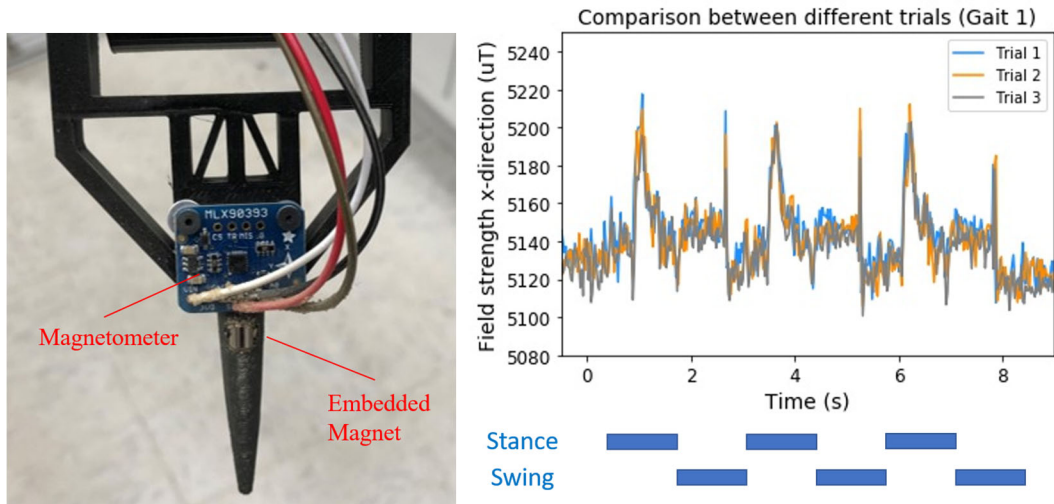


Fig. 14. Sensor embedded leg and data from leg on hard surface showing consistent peaks that correspond with stance and swing.

Results and Discussions

Grip Characterization

The original foot with the cap performed consistently in each type of sand and averaged 107% for the home position and small grip, 110% for the medium grip, and 113% for the large grip. The average was consistently in the range of 110% to 111% for each grip in both wet sand and submerged sand. The uncapped foot followed this trend; in dry sand, the averages for the no grip and small grip were the same and the robot reached 114% of the robot's weight with the medium and large grips. In wet sand, the robot achieved an average grip force of 114% in the home position, 119% in the small grip, 109% with the medium grip, and 107% with the large grips. In submerged sand, average grip forces of 110% in the home position, 114% in the small grip, 115% with the medium grip, and 117% with the large grip were obtained.

Dactyl 8 had higher weight percentages in each of the sands, reaching up to 153% of the robot's weight with a large grip in submerged sand. The averages in dry sand for the reset position, small

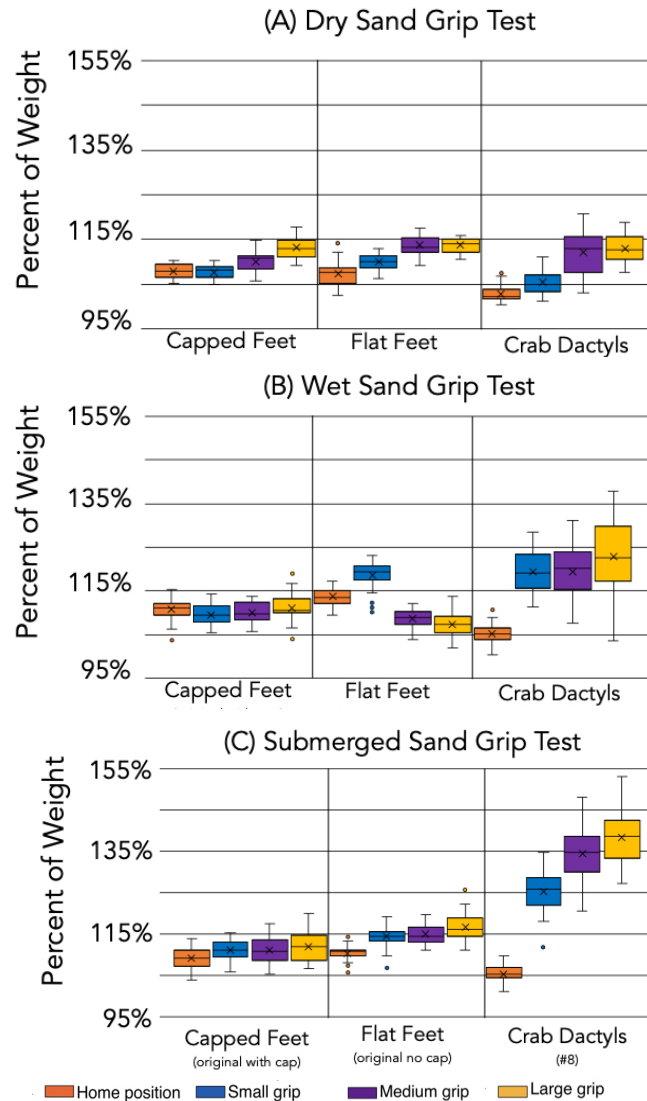


Fig. 15. After 30 trials in each configuration in (A) dry sand (B) wet sand (C) submerged sand, boxplots show that gripping is more effective with crab-like dactyls and in submerged sand.

grip, medium grip, and large grip obtained averages of 103%, 105%, 112%, and 113%, respectively. In wet sand, these values changed to 105%, 119%, 120%, and 123%. Dactyl 8 performed the best in submerged sand with averages of 105%, 125%, 134%, and 138%. The spread for Dactyl 8 is greater because the dactyl would sometimes grip very well, and other times fail to get its feet fully into the sand. Even with this spread, the robot is consistently gripping better compared to the other two types of feet. This increase in performance across each tested terrain shows that the design of Dactyl 8 performs better than the original foot with and without the cap.

The robot could experience small increases in weight due to the sand friction along with some sand stuck on the feet; however, this was addressed by calculating the weight of the robot after each run. This was done by finding the average robot weight after the winch stopped in order to incorporate any extra weight imparted by the sand. This made our testing more conservative than in [26].

A t-test (conducted in R using an alpha of 0.01) was applied to the no grip and large grip scenarios for Dactyl 8 and found that there was a significant increase in grip force for the dry sand ($p < 2.2 \times 10^{-16}$), wet sand (1.231×10^{-16}), and submerged sand ($p < 2.2 \times 10^{-16}$).

Wave Test

Wave Test 1: When comparing the three feet, Dactyl 8 had no measurable displacement at all for every grip. These results show that Dactyl 8 is better at resisting displacement (without gripping the dactyl resists displacement significantly better than the original capped foot ($p = 5.2 \times 10^{-5}$, t-test in R)). Furthermore, without the dactyl foot, gripping did not help the robot attach to the ground (Fig. 16).

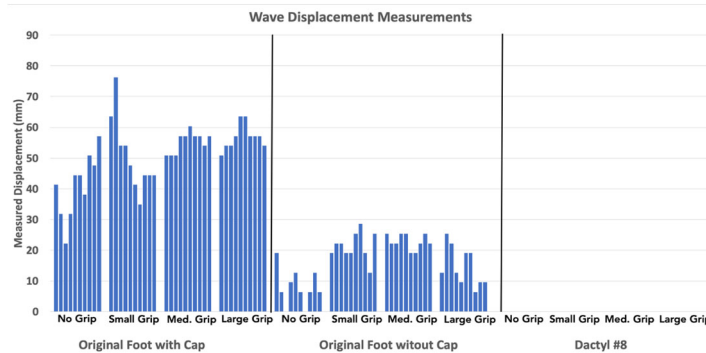


Fig. 16. The displacement results of Wave Test 1. The displacement between the capped foot, flat foot, and Dactyl 8 are due to the cross-sectional areas of the foot. The smaller the cross-sectional area, the better the foot can dig into the sand. This increase in grip ability helps the robot hold its place in the environment. There was no measurable displacement with Dactyl 8.

Wave Test 2: The robot's absolute position over time in these trials is shown in Fig. 17. After several waves, the robot experiences larger displacements because the hydrodynamic forces of the wave dislodged the robot's grip from the sand. We analyzed the average net displacement due to each wave and the total displacement after 10 waves. The average net displacement is the distance the robot travels between each wave, while the total displacement is the difference between the initial position and the displacement after the final wave. The results of the wave test for each foot is in Fig. 18.

For the original capped feet, the average net displacement per wave is -4.76mm, -5.97mm, -7.64mm, and -8.39mm for no grip, small grip, medium grip, and large grip, respectively. The standard deviations are 7.83mm, 7.82mm, 10.59mm, and 9.01mm (n = 30). After 10 waves, the total displacements are -20.46mm, -23.81mm, -32.71mm, and -32.35mm. The standard deviations are 4.72mm, 9.65mm, 2.48mm, and 8.56mm (n=3).

The performance is similar for uncapped feet. The average per wave for the original uncapped foot are -2.78mm, -2.99 mm, -5.00mm, and -5.69mm for no grip, small grip, medium grip, and large grip, respectively. The standard deviations are 3.40mm, 2.61mm, 5.90mm, and 5.94mm. The total displacement for this foot with each grip are -5.71mm, -14.69 mm, -11.48mm, and -18.31mm. The standard deviations are 4.78mm, 7.14mm, 4.83mm, and 12.38mm.

When using Dactyl 8, the total displacements are close to an order of magnitude less. The average net displacement per wave for Dactyl 8 are 0.04mm, -0.60mm, -2.05mm, and -2.35 mm for no grip, small grip, medium grip, and large grip, respectively. The standard deviations are 3.23mm, 2.92mm, 3.11mm, and 2.62mm. The total displacement for this foot with each grip is 7.36mm, 2.16mm, -4.74mm, and -1.63mm. The standard deviations are 5.43mm, 5.32mm, 5.59mm, and 7.81mm.

When comparing the results for no grip and large grip, we found that there is a statistically significant difference in the amplitude (the total distance traveled forward and backward by the robot per wave) between both the original capped and uncapped feet and Dactyl 8. For no grip, the

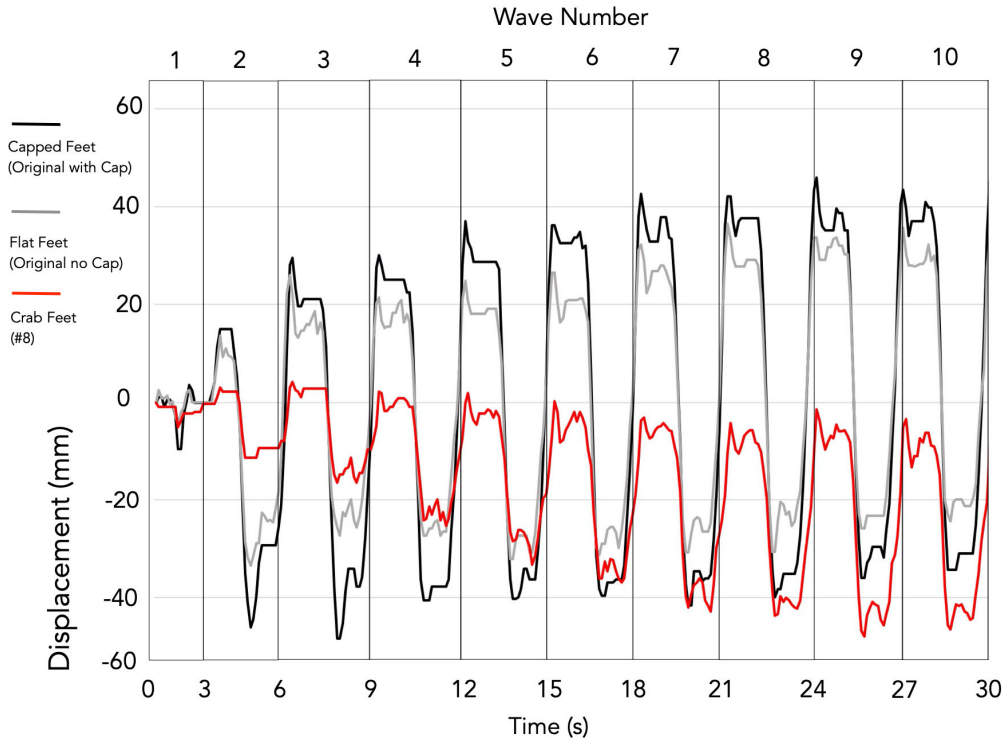


Fig. 17. The position of the robot in Wave Test 2 during 10 waves in the lab tank with a large grip. The displacement amplitudes are greatest with the original leg with the cap, are lessened with the original uncapped foot, and are the smallest with Dactyl 8. The displacements between each wave along with the total displacement from before the first wave to the end of the last wave also follow this trend. The displacements for all feet are in Appendix A.

p-value corresponding to the difference in amplitudes between Dactyl 8 and the original capped foot was 2.2×10^{-16} and between Dactyl 8 and the original uncapped foot resulted in a p-value of 1.36×10^{-3} . For the large grip, the p-value corresponding to the difference in amplitude between Dactyl 8 and the original capped foot was 2.2×10^{-16} , and between Dactyl 8 and the original uncapped foot was 7.8×10^{-6} . All four p-values lead to the conclusion that the foot type, whether it be original capped, original uncapped, or Dactyl 8, has a statically significant impact on the amplitude. These p-values also show that Dactyl 8 significantly minimized the amplitude of the displacements caused by the waves.

These results (found in R with ANOVA tests) show that Dactyl 8 is significantly better at resisting displacement than the other feet for all of the grips (no grip: $p=1.47 \times 10^{-3}$, small grip: $p=1.54 \times 10^{-2}$, medium grip: $p=1.04 \times 10^{-4}$, large grip: $p=2.39 \times 10^{-2}$). Overall, there is a significant difference in performance between the dactyl and the other two feet.

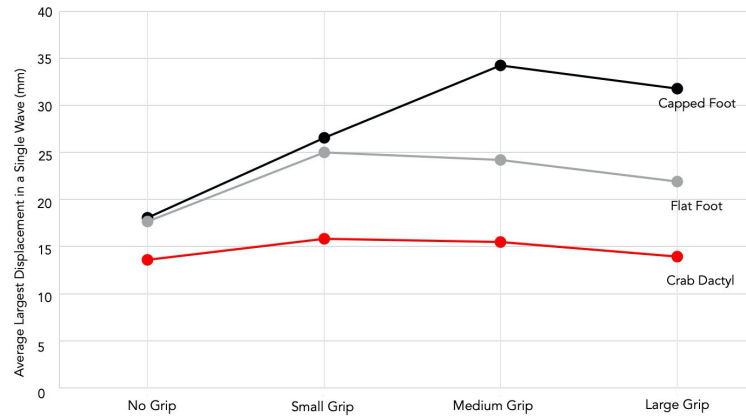


Fig. 18. The displacement per wave averaged over 30 waves (reset every 10 waves) for each grip and foot type, shows that crab-like dactyls decrease displacement even when waves dislodge robot.

Locomotion Test

The robot was able to walk with each type of foot on all of the materials at all of the speeds except for Dactyl 8 with the fast gait on linoleum (Fig. 19). There is not enough friction between Dactyl 8 and the linoleum at the fast gait speed to allow the robot to move forward. Even though the robot is still able to move, the velocity is slowed when using Dactyl 8 by about 37% on linoleum, 58%, 67% and 28% for dry, wet, and submerged sand, respectively, and 61% in the rock bed.

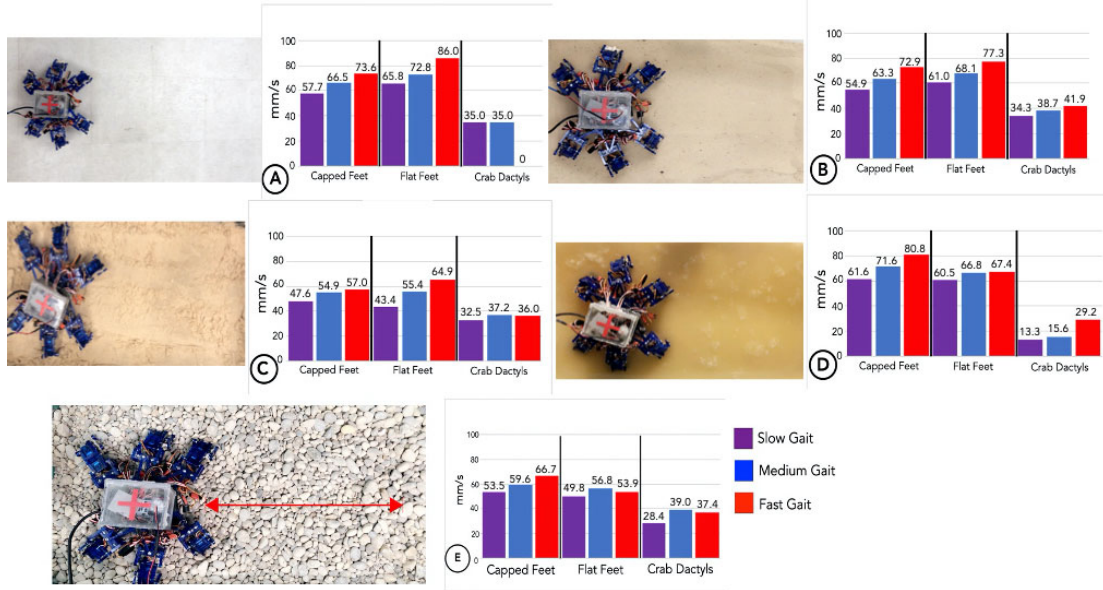


Fig. 19. The robot's speed was evaluated on several different substrates (n=15): hard smooth linoleum tile (A), dry sand (B) wet sand, (C) and submerged sand with 25.4mm of water above sand line which is enough to completely submerge feet of the robot (D), and rock bed (E).

In order to compare the walking ability of different robots the Hexy robot, Sebastian robot, Klann 1, and Klann 2 are tested on dry sand for average speed. The Sebastian and Hexy robots were tested using an alternating tripod gait over 18 inches (457.2mm) for ten trials. The average of their speeds were taken, and are recorded in Table 7. The Klann 1 and Klann 2 robots had a set rotation velocity on their motors, resulting in a constant speed of motion for the robot. The speeds from the trials of these robots are in Table 7.

Table 7. SPEED OF DIFFERENT ROBOTS ON DRY SAND

Robot	Speed
Hexy	86.0 mm/s
Sebastian	13.5 mm/s
Klann 1	78.0 mm/s
Klann 2	60.5 mm/s

Freshwater Beach Testing

To demonstrate the feasibility of our amphibious platform robots to walk on tough terrains, the Hexy robot and Klann 2 were tested on beaches in shallow water.

1. Hexy Test

The Hexy robot was tested on a rocky beach (Mentor Headlands) and on a sandy beach (Edgewater Park Cleveland) (Fig. 20). On the rocky beach, the robot was able to walk into waves of frequency (approximately 0.35 Hz) on a day with wind speed (3 mph) where the average wave height was half the height of the robot (approximately 9 cm). On the sandy beach, the robot was able to walk into waves of frequency (approximately 0.23Hz) on a day with wind speed (10mph) into depths where the average wave height was equal to robot body height (18 cm).



Fig. 20. A. Hexy holding its position on rocky beach B. Hexy walking into the water at sandy beach

At deeper depths the robot floats, which was in part a limitation of fabrication during pandemic conditions. With a robot weight of 1347 g and displaced volume of 1770 cm³, the volume would have to be reduced by 24% (434 cm³) to be neutrally buoyant with density equal to freshwater at 1 g/cm³. Alternatively, 434 g (31.4% of Hexy weight) could be added to the mass. However reducing volume is likely to be more advantageous because it would not increase sinkage in sand. As shown in Table 5, it is likely that all of this volume can come from electronics compartment.

Table 5.

MEASUREMENT OF HEXY ROBOT

	Structure components (Legs and base)	Electronic compartments (Onboard batteries and control boards)	Total Hexy Robot
Weight	693.9 g	653.1 g	1347 g
Volume	800 cm ³	970 cm ³	1770 cm ³

2. Klann 1 Test

The purpose of the Klann 1 robot was to incorporate leg compliance into the design. The force gauge measures the total vertical forces, reflecting the sum total of all of the forces on the dactyls. Grip testing was performed 15 times on dry sand with and without compliance. The average vertical force with compliance is 1,091 gf, and the average vertical force without compliance is 1105 gf. These results are not statistically different, however, it may be that future improvements can be made, varying the spring stiffness and the length of travel. Also, in this preliminary grip test, Klann 1 was not equipped with tapered dactyls, and the test was performed in dry sand, where differences were small compared to wet sand because this robot is not fully waterproofed. It may be more valuable on rocky surfaces.

3. Klann 2 Test



Fig. 21. Klann 2 robot walking at 1 meter depth in shallow inland lake

The Klann 2 robot is neutrally buoyant, but Klann legs alone do not grip the ground, as shown in grip test 1. Thus it required an additional weight. The weight adds 30% to the dry weight of the robot (Table 6). This is similar to the additional percentage gripping the ground can gain.

With this additional weight it is able to walk completely submerged (see Fig. 21). The locomotion test was performed by placing the robot at the shore and controlling it with a remote control to walk into the water. Klann 2 was able to walk into calm water with little wind on a sandy beach of Squam Lake in Holderness, NH, traversing approximately 30 feet from the shore until it reached a final depth of approximate 3 feet. The depth was limited by the transmission of the control signal. When this test was reproduced in Lake Erie, we found that the robot could not maneuver in dry sand with the addition of the weight. This shows that the small increase in weight due to gripping is critical for amphibious robots. We believe with more testing, we can achieve gripping also with the Klann robot.

Table 6.

MEASUREMENT OF KLANN 2

	Structure components (Legs and base)	Electronic compartments (Onboard batteries and control boards)	Klann 2 Robot	Added weight (Aluminum block)	Weighted Klann 2 Robot
Weight	1145 g	1315 g	2460 g	748 g	3208 g
Volume	924 cm ³	1526 cm ³	2450 cm ³	277 cm ³	2727 cm ³

Summary Discussion

Dragging the legs inward increases the penetration depth of the dactyl in the sand, and as a result, the sand around the dactyl resists lifting. Conceptually, just a like boat's anchor slides deeper into the ground when pulled along the surface, the combination of inward motion and foot shape are important for robots. Furthermore, just like anchors are stable (hard to extract) with appropriate scope (when tension force has large tangential component) and yet recoverable (easier to extract) when the boat is directly above anchor (when tension force is primarily vertical), robots in these environments need to be able to take advantage of directional properties of kinematics and mechanics in granular media.

It our goal to understand this more with modeling. Originally most models are for wheeled and tracked vehicles, but they have been in some cases been successfully extended for simple legged robots [76], [77]. In resistive force theory (RFT), the essential soil properties include packing density and a viscosity term [76], [78]. RFT enables the summation of force contributions from individual geometric surfaces moving through soil at different speeds, angles, and depths.

Scaling relationships that come from these geotechnical relationships are a goal for our future work. Because crabs grow while maintaining the same essential shape and because a wide range of crab sizes thrive in nature (from 12ft spider crabs to half inch pea crabs), we expect that crab-like robots can similarly scale. In engineered devices, the same boat anchors are used for both oceans and freshwater lakes, with recommendations for rocky/muddy/sandy bottoms and with anchor size scaling nonlinearly with boat length [79].

A preliminary understanding of the problem can built from the following considerations. On dry substrates weight causes sinkage, which can be sufficient to prevent locomotion. In surf zones, weight is needed to stabilize robot against hydrodynamic wave force, which can be sufficient to displace or overturn robot. Any weight that can be "saved" by grasping the ground in wet sand will reduce sinkage in dry sand. For example, approximations based on [80] suggest that reducing weight by 33% will reduce sinkage by 11% since sinkage will be proportional to weight to the power of a soil-dependent constant C .

Practically, an amphibious robot design can accommodate a limited range of wheel or dactyl depths (too deep results in a stall, too shallow result in loss of traction). If the goal is to operate in the widest range of conditions, then ideally the ratio of wet-to-dry sinkage is 1 or a little greater. If the kinematics are the same, the ratio of wet sinkage to dry sinkage can be approximated with the relative densities of the robot as:

$$\frac{\text{sinkage depth in water}}{\text{sinkage depth on land}} = \frac{(\rho_{\text{robot}} - \rho_{\text{water}})C_{\text{wet}}}{(\rho_{\text{robot}})C_{\text{dry}}}$$

Note that this relationship is appropriate for any size robot where viscous forces dominate [80]. The volume and wheel geometry parameters drop out because we are assuming the same robot in both terrains. While the sinkage parameters of the robot can be different on the wet and dry part of the beach (thus $C_{\text{dry}} \neq C_{\text{wet}}$), we cannot control those parameters in design. We can only control robot density. In order to get wet-to-dry sinkage ratio of close to 1, this suggests a preference for high-density robots relative to the density of water. However, usually robots are designed for low density for a variety of reasons (material cost, energetics, inertia, etc.).

Thus, varying sinkage through inward kinematic motions is important because it enables lower weight robots (with low density) that escape the limitations of the above equation. Even for wheeled robots, gait options enabled by additional degrees of freedom (e.g. push-pull locomotion demonstrated by 312kg Scarab robot [81]) can vary sinkage. For neutrally buoyant or lighter amphibious legged robots, this suggests the following design considerations

- Geometry to handle varying sinkage (e.g. tapered dactyls)
- Kinematic motions in wet terrain to increase sinkage
- Minimal tangential motions relative to dry terrain to decrease sinkage
- High power-to-weight servos to explore range of possible kinematic motions and maximize payload capacity

If passive mechanisms enable reduced actuation, resulting robots will be simpler¹. If articulated robot legs are required, resulting robots will be able to vary gait to modify force distribution², and mimic hand-like grasping maneuvers³, but will require active substrate characterization⁴, more complex gait optimization⁴, and more precise geotechnical modeling relationships⁵. These are precisely the topics our team plans to explore in their PhD theses.

¹Yifeng Gong

²Nicole Graf

³Tom Zhou

⁴John Grezmak

⁵Chunchu Zhu

Conclusions and Implications for Future Research/ Implementation

This work shows that crab-like legs can be beneficial for surf zone robots to address the challenges of sandy terrain, wave disruptions and potential obstacles. When the feet penetrate deeper into the sand, extraction forces are increased and displacement due to waves are reduced. Preliminary versions of these results are interesting for mechanics of granular media, biology, and robotics (we have presented at conferences reflecting this [26], [28] including one conference where we were tied for 3rd place (<http://uasr.xjtu.edu.cn/info/1053/2033.htm>) and our results are in revision with *Bioinspiration and Biomimetics* (the best journal specifically for bio-inspired robotics, impact factor 3).

Proving this concept of “grasping the ground” was successful and will enable lighter amphibious robots. If pulling inward to engage feet increases the effective weight in very shallow water by one third, then the robot that pulls inward can be 75% of the weight of a similar robot that does not. When that lighter robot emerges from the water to walk on dry sand, it can do so more efficiently both because cost of transport typically scales with mass and also because it sinks into the sand less. Specifically, our test with Klann legs show that carrying an additional 30% weight makes it hard for the robot to walk in dry sand. Thus, since grasping reduces weight required, it could enable otherwise infeasible legged robots. Even small reduction in required weight reduces battery requirements, which would in turn increase mission length. Future robots could grasp the ground intermittently, perhaps using wave forces for locomotion, increasing efficiency even further (Fig. 22).

We believe follow-on projects will enable a robot that can walk from dry sand into waves into greater than meter depth water. Using legs instead of tracks, fins, or wheels used by other amphibious robots [1]–[5], [25] could better enable traversal of rough, uneven terrain. The key will be reducing the volume the robot displaces in water so that the same weight of robot will have density equal to or greater than water. Specifically, as fabrication facilities reopen after the 2020 pandemic, robot components can be swapped from 3D printed parts to machined metal and plastic parts increasing density and strength. Additionally, machined tolerances will allow us to create more compact enclosures for electronic components. Another strategy can be adding more legs to decrease the ground pressure on sand (while six legs is the minimum for ground walking with stable tripods, crabs are decapods with ten legs which enables more distributed ground forces when needed).

For practical implementations, it will be critical to determine the simplest effective legs for anchoring. This project has identified several critical parameters (foot shape, foot trajectory, number of feet, body power-to-volume) that can be optimized. In future, our prototypes can be used to compare articulated legs with simpler wheel legs or reduced actuation mechanisms such as Klann mechanisms. We expect that augmenting these simple mechanisms with passive compliance and custom feet shapes will show increased grip forces which will ultimately enable better performance in waves and sand. If so, simpler legs can be easily added to other devices to create walking sensor beds, quadcopters that can walk or reposition after landing, diver-following tool chests, or modular swarms of amphibious robots.

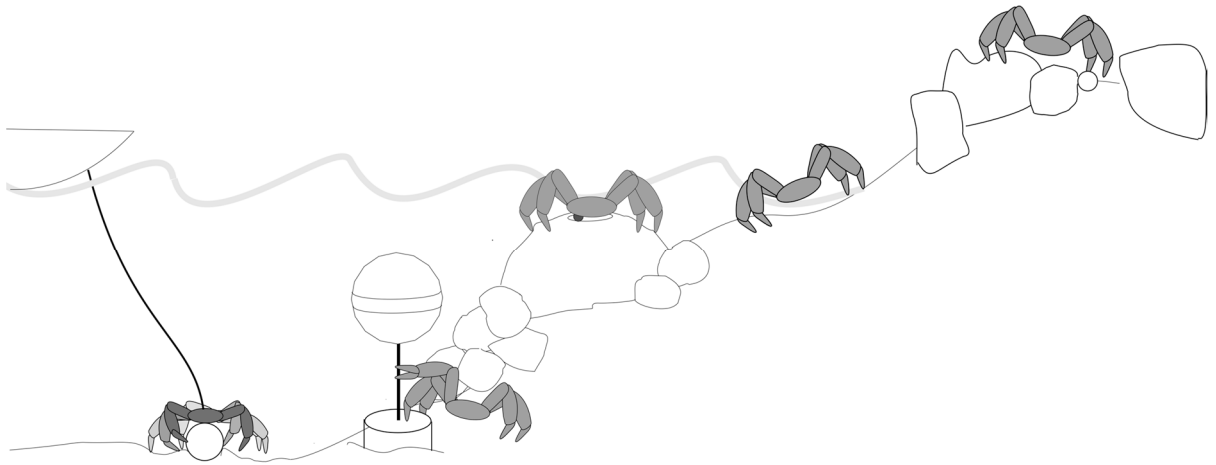


Fig. 22. Amphibious robot concepts that can be used to respond to munition. Such robots can be deployed from either a boat or from a beach.

A more in-depth analysis of requirements for grasping in response to waves would also be valuable in addressing unanswered questions such as: For trafficability and energy efficiency, when is it better to use small legs versus large wheels? Can mechanics models assess feasibility for particular mission lengths and conditions a priori? Can detailed mechanics models be used to determine best dactyl shapes to take advantage of particular environments? An additional benefit could be in understanding more about how biological crabs are likely to be affected by ecological changes.

Direct applications of this work can include novel mobile robots in two categories. First, crab-like legged robots can be deployed on a tether from a surface boat to investigate or retrieve objects previously detected by towed or overhead surveys. Testing of a preliminary robot like this would require developing additional data analysis for leg sensors, adding a reinforced tether, developing control for spiral searching maneuvers, and refinements of robotic legs to grasp and lift target objects. Second, this work could be applied to robots that need to travel along beaches, sandbars, and waterlines. Such robots could be integral to environmental clean-up because they are light enough to be deployed from the air and low enough to the ground to take surface samples, operate under docks, or even unbury partially covered munitions.

Works Cited

- [1] Y. Sun and S. Ma, “A versatile locomotion mechanism for amphibious robots: Eccentric paddle mechanism,” *Adv. Robot.*, vol. 27, no. 8, pp. 611–625, Jun. 2013.
- [2] “J8 Atlas Xtreme Terrain Robot (XTR) - Army Technology.” [Online]. Available: <https://www.army-technology.com/projects/j8-atlas-xtreme-terrain-robot-xtr/>. [Accessed: 02-Jun-2020].
- [3] A. S. Boxerbaum, P. Werk, R. D. Quinn, and R. Vaidyanathan, *Design of an autonomous amphibious robot for surf zone operation: Part I mechanical design for multi-mode mobility*, vol. 2. 2005.
- [4] B. Han, X. Luo, X. Wang, and X. Chen, “Mechanism design and gait experiment of an amphibian robotic turtle,” *Adv. Robot.*, vol. 25, no. 16, pp. 2083–2097, Jan. 2011.
- [5] “C-2 Innovations, Inc (C-2i) - weepprojects.” [Online]. Available: <https://www.weepprojects.com/c-2-innovations-inc-c-2i.html>. [Accessed: 02-Jun-2020].
- [6] J. Slonaker *et al.*, “General scaling relations for locomotion in granular media,” *Phys. Rev. E*, vol. 95, no. 5, p. 52901, Sep. 2017.
- [7] S. Chopra, M. T. Tolley, and N. Gravish, “Granular Jamming Feet Enable Improved Foot-Ground Interactions for Robot Mobility on Deformable Ground,” *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 3975–3981, 2020.
- [8] E. Lathrop, I. Adibnazari, N. Gravish, and M. T. Tolley, “Shear Strengthened Granular Jamming Feet for Improved Performance over Natural Terrain,” 2020.
- [9] G. Sartoretti, S. Shaw, K. Lam, N. Fan, M. Travers, and H. Choset, “Central Pattern Generator with Inertial Feedback for Stable Locomotion and Climbing in Unstructured Terrain.”
- [10] E. Tennakoon, “Probe-before-step walking strategy for multi-legged robots on terrain with risk of collapse - Robotics and Autonomous Systems Group,” 09-Mar-2020. [Online]. Available: <https://research.csiro.au/robotics/paper-probe-before-step-walking-strategy-for-multi-legged-robots-on-terrain-with-risk-of-collapse/>. [Accessed: 30-Jul-2020].
- [11] J. Ayers and J. Witting, “Biomimetic approaches to the control of underwater walking machines,” *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 365, no. 1850, pp. 273–295, Jan. 2007.
- [12] M. M. Martinez, “Running in the surf: Hydrodynamics of the shore crab *Grapsus tenuicrustatus*,” *J. Exp. Biol.*, vol. 204, no. 17, pp. 3097–3112, Sep. 2001.

- [13] A. Mahapatra, S. S. Roy, D. Pratihari, and D. Pratihari, *Inverse Dynamics and Feet-Terrain Collision Model for Optimal Distribution of the Contact Forces During Crab Motion of a Hexapod Robot*. 2016.
- [14] A. Mahapatra, S. S. Roy, and D. K. Pratihari, "Optimal Feet-Forces' and Torque Distributions of Six-Legged Robot Maneuvering on Various Terrains," *Robotica*, vol. 38, no. 6, pp. 1041–1063, 2020.
- [15] Khan, Liquan, Gang, Imran, Waqas, and Zaidi, "Concept Design of the Underwater Manned Seabed Walking Robot," *J. Mar. Sci. Eng.*, vol. 7, no. 10, p. 366, Oct. 2019.
- [16] A. Mahapatra, S. S. Roy, and D. K. Pratihari, "Study on feet forces' distributions, energy consumption and dynamic stability measure of hexapod robot during crab walking," *Appl. Math. Model.*, vol. 65, pp. 717–744, Jan. 2019.
- [17] G. Krummel, K. N. Kaipa, and S. K. Gupta, "A horseshoe crab inspired surf zone robot with righting capabilities," *Proceedings of the ASME Design Engineering Technical Conference*, vol. 5A. 17-Aug-2014.
- [18] B. K. Jun, Bong-Huan, Hyungwon Shim, "Huge Six-Legged Robot Crabster Goes Swimming - IEEE Spectrum," 2013. [Online]. Available: <https://spectrum.ieee.org/automaton/robotics/industrial-robots/six-legged-underwater-robot-crabster>. [Accessed: 02-Jun-2020].
- [19] H. Greiner, A. Shtetman, Chikyung Won, R. Elsley, and P. Beith, "Autonomous legged underwater vehicles for near land warfare," in *Proceedings of Symposium on Autonomous Underwater Vehicle Technology*, 1996, pp. 41–48.
- [20] R. J. Full, "Using biological inspiration to build artificial life that locomotes," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2001, vol. 2217, pp. 110–120.
- [21] C. Cui, Y. Luo, J. Zeng, X. Shang, and J. Du, "Kinematic Analysis and Simulation of Walking Leg of Bionic Amphibious Crab-Like Robot," in *2020 6th International Conference on Control, Automation and Robotics (ICCAR)*, 2020, pp. 762–767.
- [22] A. J. Ijspeert, "Central pattern generators for locomotion control in animals and robots: A review," *Neural Networks*, vol. 21, no. 4, pp. 642–653, 2008.
- [23] G. Wang, X. Chen, and S.-K. Han, "Central pattern generator and feedforward neural network-based self-adaptive gait control for a crab-like robot locomoting on complex terrain under two reflex mechanisms," *Int. J. Adv. Robot. Syst.*, vol. 14, no. 4, p. 1729881417723440, Jul. 2017.
- [24] C. W. Cunningham, N. W. Blackstone, and L. W. Buss, "Evolution of king crabs from hermit crab ancestors," *Nature*, vol. 355, no. 6360, pp. 539–542, 1992.
- [25] P. Energy, "Pliant Energy Home." [Online]. Available: <https://www.pliantenergy.com>.
- [26] N. M. Graf, A. M. Behr, and K. A. Daltorio, *Crab-Like Hexapod Feet for Amphibious Walking in Sand and Waves*, vol. 2. Living Machines, Springer International Publishing, 2019.
- [27] N. M. Graf, A. M. Behr, and K. A. Daltorio, "In Revision - Dactyls and Gripping Stance for Amphibious Crab-like Robots in Sandy Substrates," *Bioinspir. Biomim.*, 2020.
- [28] N. M. Graf, A. M. Behr, and K. A. Daltorio, "Stability of a Crab-Like Amphibious Robot in on Sandy Surfaces," *Engineering Mechanics Institute (EMI)*. Caltech, California., 2019.
- [29] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, "Review of fish swimming modes for aquatic locomotion," *IEEE J. Ocean. Eng.*, vol. 24, no. 2, pp. 237–252, 1999.
- [30] T. Horvat, K. Karakasiliotis, K. Melo, L. Fleury, R. Thandiackal, and A. J. Ijspeert, "Inverse kinematics and reflex based controller for body-limb coordination of a salamander-like robot walking on uneven terrain," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 195–201.

- [31] T. Horvat, K. Melo, and A. J. Ijspeert, "Spine Controller for a Sprawling Posture Robot," *IEEE Robot. Autom. Lett.*, vol. 2, no. 2, pp. 1195–1202, 2017.
- [32] Y. Junzhi, D. Rui, Y. Qinghai, T. Min, W. Weibing, and Z. Jianwei, "On a Bio-inspired Amphibious Robot Capable of Multimodal Motion," vol. 17, no. 5, Sep. 2012.
- [33] A. Mehringer, A. Kandhari, H. Chiel, R. Quinn, and K. Daltorio, "An Integrated Compliant Fabric Skin Softens, Lightens, and Simplifies a Mesh Robot BT - Biomimetic and Biohybrid Systems," 2017, pp. 315–327.
- [34] D. Zarrouk, M. Mann, N. Degani, T. Yehuda, N. Jarbi, and A. Hess, "Single actuator wave-like robot (SAW): design, modeling, and experiments," *Bioinspir. Biomim.*, vol. 11, no. 4, p. 46004, 2016.
- [35] R. Harkins, J. Ward, R. Vaidyanathan, A. S. Boxerbaum, and R. D. Quinn, "Design of an autonomous amphibious robot for surf zone operations: Part II - Hardware, control implementation and simulation," in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, 2005, vol. 2, pp. 1465–1470.
- [36] G. Dudek *et al.*, "AQUA: An Amphibious Autonomous Robot," *Computer (Long. Beach. Calif.)*, vol. 40, no. 1, pp. 46–53, 2007.
- [37] G. Dudek *et al.*, "A visually guided swimming robot," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 3604–3609.
- [38] C. Georgiades *et al.*, "AQUA: an aquatic walking robot," in *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566)*, 2004, vol. 4, pp. 3525–3531 vol.4.
- [39] B. B. Dey, S. Manjanna, and G. Dudek, "Ninja legs: Amphibious one degree of freedom robotic legs," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 5622–5628.
- [40] D. Drotman, S. Jadhav, M. Karimi, P. deZonia, and M. Tolley, "3D printed soft actuators for a legged robot capable of navigating unstructured terrain," *2017 IEEE Int. Conf. Robot. Autom.*, 2017.
- [41] A. Hiller, C. A. Viviani, and B. Werding, "Hypercarcinisation : an evolutionary novelty in the commensal porcellanid *Allopetrolisthes spinifrons* (Crustacea : Decapoda : Porcellanidae)," Sep. 2010.
- [42] M. M. Martinez, R. J. Full, and M. A. R. Koehl, "Underwater punting by an intertidal crab: A novel gait revealed by the kinematics of pedestrian locomotion in air versus water," *J. Exp. Biol.*, vol. 201, no. 18, pp. 2609–2623, Sep. 1998.
- [43] S. Kim, J. E. Clark, and M. R. Cutkosky, "iSprawl: Design and Tuning for High-speed Autonomous Open-loop Running," *Int. J. Rob. Res.*, vol. 25, no. 9, pp. 903–912, Sep. 2006.
- [44] S. A. Bailey, J. G. Cham, M. R. Cutkosky, and R. J. Full, "Comparing the Locomotion Dynamics of the Cockroach and a Shape Deposition Manufactured Biomimetic Hexapod BT - Experimental Robotics VII," 2001, pp. 239–248.
- [45] J. M. Hemmi and D. Tomsic, "Differences in the escape response of a grapsid crab in the field and in the laboratory," *J. Exp. Biol.*, vol. 218, no. Pt 21, pp. 3499–3507, 2015.
- [46] M. M. MARTINEZ, "Issues for Aquatic Pedestrian Locomotion1," *Am. Zool.*, vol. 36, no. 6, pp. 619–627, Sep. 1996.
- [47] M. Calisti, E. Falotico, and C. Laschi, "Hopping on Uneven Terrains With an Underwater One-Legged Robot," *IEEE Robot. Autom. Lett.*, vol. 1, no. 1, pp. 461–468, 2016.
- [48] J. Ayers, "Underwater walking," *Arthropod Struct. Dev.*, vol. 33, pp. 347–360, Aug. 2004.
- [49] K. K. Şafak and G. G. Adams, "Dynamic Modeling and Hydrodynamic Performance of

- Biomimetic Underwater Robot Locomotion,” *Auton. Robots*, vol. 13, no. 3, pp. 223–240, Sep. 2002.
- [50] “Inside Adam Savage’s Cave: The Robugtix T8 Spider! - Tested.com,” *Tested*. 15-Sep-2020.
 - [51] D. R. Elsley *et al.*, “Autonomous legged underwater vehicles for near land warfare,” in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium, Naval Postgraduate School*, 1995, pp. 4–7.
 - [52] J. C. Klann, “United States Patent: 6260862 - Walking device,” 15-Sep-2001.
 - [53] S. Nansai, N. Rojas, M. R. Elara, R. Sosa, and M. Iwase, “On a Jansen leg with multiple gait patterns for reconfigurable walking platforms,” *Adv. Mech. Eng.*, vol. 7, no. 3, p. 1687814015573824, Sep. 2015.
 - [54] D. F. Giesbrecht, “Design and optimization of a one-degree-of-freedom eight-bar leg mechanism for a walking machine,” *undefined*. 15-Sep-2010.
 - [55] J. K. Sheba, E. Martínez-García, M. R. Elara, and L. Tan-Phuc, “Design and evaluation of reconfigurable Klann mechanism based four legged walking robot,” in *2015 10th International Conference on Information, Communications and Signal Processing (ICICS)*, 2015, pp. 1–5.
 - [56] N. Lokhande and V. B. Emche, “Mechanical Spider by Using Klann Mechanism,” 2013.
 - [57] W. Thielicke, “Klann Linkage in Phun - Walking Robot - YouTube.” 15-Sep-2020.
 - [58] K. Hauser, T. Bretl, J.-C. Latombe, K. Harada, and B. Wilcox, “Motion Planning for Legged Robots on Varied Terrain,” *Int. J. Rob. Res.*, vol. 27, no. 11–12, pp. 1325–1349, Sep. 2008.
 - [59] X. Chen, L. Wang, X. Ye, G. Wang, and H. Wang, “Prototype development and gait planning of biologically inspired multi-legged crablike robot,” *Mechatronics*, vol. 4, no. 23, pp. 429–444, Sep. 2013.
 - [60] Y. Peng, “Research on walking mechanism analysis and control system of a crab-like biologically inspired robot,” Harbin Engineering University, 2003.
 - [61] R. E. Ritzmann, R. D. Quinn, J. T. Watson, and S. N. Zill, “Insect Walking and Biorobotics: A Relationship with Mutual Benefits,” *Bioscience*, vol. 50, no. 1, pp. 23–33, Sep. 2000.
 - [62] R. Beer, H. Chiel, R. Quinn, K. Espenschied, and P. Larsson, “A Distributed Neural Network Architecture for Hexapod Robot Locomotion,” *Neural Comput.*, vol. 4, pp. 356–365, May 1992.
 - [63] N. Szczecinski, A. Getsy, J. Martin, R. Ritzmann, and R. Quinn, “Mantisbot is a robotic model of visually guided motion in the praying mantis,” *Arthropod Struct. Dev.*, vol. 46, Mar. 2017.
 - [64] K. A. Daltorio, A. S. Boxerbaum, A. D. Horchler, K. M. Shaw, H. J. Chiel, and R. D. Quinn, “Efficient worm-like locomotion: slip and control of soft-bodied peristaltic robots,” *Bioinspir. Biomim.*, vol. 8, no. 3, p. 35003, Sep. 2013.
 - [65] A. Kandhari, A. D. Horchler, G. S. Zucker, K. A. Daltorio, H. J. Chiel, and R. D. Quinn, “Sensing Contact Constraints in a Worm-like Robot by Detecting Load Anomalies,” 2016, pp. 97–106.
 - [66] A. Kandhari, R. Quinn, H. Chiel, and K. Daltorio, “ICRA 2018,” 2018.
 - [67] H. Yousef, M. Boukallel, and K. Althoefer, “Tactile sensing for dexterous in-hand manipulation in robotics-A review,” *Sensors Actuators A Phys.*, vol. 167, no. 2, pp. 171–187, Sep. 2011.
 - [68] Z. Kappassov, J.-A. Corrales, and V. Perdereau, “Tactile sensing in dexterous robot hands — Review,” *Rob. Auton. Syst.*, vol. 74, pp. 195–220, Sep. 2015.
 - [69] M. Yuen, A. Cherian, J. C. Case, J. Seipel, and R. K. Kramer, “Conformable actuation and sensing with robotic fabric,” in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2014, pp. 580–586.
 - [70] M. Totaro, A. Mondini, A. Bellacicca, P. Milani, and L. Beccai, “Integrated Simultaneous Detection of Tactile and Bending Cues for Soft Robotics,” *Soft Robot.*, vol. 4, no. 4, pp. 400–410, Sep. 2017.

- [71] D. W. Haldane *et al.*, “Integrated Manufacture of Exoskeletons and Sensing Structures for Folded Millirobots,” *J. Mech. Robot.*, vol. 7, no. 2, Sep. 2015.
- [72] X. A. Wu, T. M. Huh, R. Mukherjee, and M. Cutkosky, “Integrated Ground Reaction Force Sensing and Terrain Classification for Small Legged Robots,” *IEEE Robot. Autom. Lett.*, vol. 1, no. 2, pp. 1125–1132, 2016.
- [73] K. Walas, “Terrain Classification and Negotiation with a Walking Robot,” *J. Intell. Robot. Syst.*, vol. 78, no. 3, pp. 401–423, Sep. 2015.
- [74] G. D. Wile *et al.*, *Screenbot: Walking inverted using distributed inward gripping*. 2008.
- [75] N. Rojas and F. Thomas, “On closed-form solutions to the position analysis of Baranov trusses,” *Mech. Mach. Theory*, vol. 50, pp. 179–196, 2012.
- [76] C. Li, T. Zhang, and D. I. Goldman, “A terradynamics of legged locomotion on granular media,” *Science (80-.)*, vol. 339, no. 6126, pp. 1408–1412, 2013.
- [77] A. S. Baumgarten and K. Kamrin, “A general constitutive model for dense, fine-particle suspensions validated in many geometries,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 116, no. 42, pp. 20828–20836, 2019.
- [78] C. E. Brennen, *Internet Book on Fluid Mechanics*. Danks Publishing, 2016.
- [79] “<https://www.lewmar.com/sites/default/files/DTX%20&%20Delta%20Anchor%20specifications.pdf>.” .
- [80] L. Ding, Haibogao, YuankaiLi, GuangjunLiu, and ZongquanDeng, “Improved explicit-form equations for estimating dynamic wheel sinkage and compaction resistance on deformable terrain,” *Mech. Mach. Theory*, vol. 86, pp. 235–264, 2015.
- [81] C. Creager, K. Johnson, M. Plant, S. Moreland, and K. Skonieczny, “Push-pull locomotion for vehicle extrication,” *J. Terramechanics*, vol. 57, pp. 71–80, 2015.

Appendix A: Total Wave Test Displacement Performance

