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SEAL Pack
Versatile, Portable, and Rapidly Deployable SEa, Air, and Land Vehicle

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***Abstract*—There are thirteen categories in the Robotic USAR ontology covering land air and sea vehicles. We present a robot system that is capable of four of those categories including aerial, terrestrial and marine locomotion in a single package that is man-portable and low cost. Each mode of locomotion has useful capabilities that the others do not. The land vehicle can travel over 5km with a 500g load. The boat can travel 0.5 km over water or loiter for 140 minutes. The flyer can traverse any terrain for short periods of time. The system packs into a small $33 \times 20 \times 14$ cm package weighing 1 kg. We present design issues and experimental verification.**

I. Introduction

Disaster environments encountered by robotic first responders vary widely. Disaster sites may include a rubble pile from a collapsed building or water flooding in a nuclear power plant emergency like Fukushima [1]. This variety requires robots that can traverse sea, air, and land. however, the space and weight constraints for first responders make it difficult to transport many robotic devices and associated control equipment. To address transportation issues, an ideal robotic system would be one that could have all three modalities, have a small form factor, and be light weight.

Schlenoff et al. present an ontology for Robotic USAR [2]. In it, they include 13 robot categories based on roles and deployment loosely grouped into ground, aerial, and aquatic vehicles. We present a system that can transform into all three. This system can be categorized in the robot ontology as follows:

- #3 Ground: Non-Collapsed Structure-Wide Area Survey
- #9 Aerial: Rooftop Payload Drop
- #10 Aerial: Ledge Access
- #13 Aquatic: Swift Water Surface Swimmer

Robotic unmanned aerial vehicles (UAV) can be particularly useful for situational awareness of a disaster and can help in command and control. Murphy et al. have shown examples of this using UAVs [3]. There are a variety of robotic land vehicles used for search and rescue [4]. Primarily, these vehicles stress mobility over rough terrain as well as specific functionality such as water delivery for combating fire [5], or flexible snake-like cameras [6], etc. Murphy also explored the use of an unmanned aquatic surface vehicle to help in the aftermath of a hurricane [3] to inspect the integrity of seawalls, and piers in the littoral zone.

One approach to achieving locomotion versatility is to use reconfigurable robotic modules. In 1988, Fukuda and Nakagawa developed the "Dynamically Reconfigurable Robotic System"[7]. Since their seminal contribution, the field of modular robotics has offered the promise that by interconnecting a large number of similar or identical modules, robots may be built specifically for each task at hand, thereby meeting unknown challenges by reconfiguration in situ [8].

In previous work [9], we have shown that the mass and power budget required for supporting the construction of the robot entirely from reconfigurable modules, as well as the reliability issues arising from the complexity of the modules, present a nearly insurmountable obstacle to practical deployments of modular robots. In that work and in following work by [10] a solution was presented to fabricate a robot body made of passive materials on-the-fly thereby allowing mass, power, and complexity to be concentrated in modules that perform useful tasks. Both approaches compare favorably with dynamically reconfigurable robots in their ability to address an unknown challenge in a robotic mission. In [9] we also note the value of combining an in situ produced body with modules in robot supported missions where human operators are on hand. A similar approach was explored in LocoKit by Larsen et al., who developed the framework of layered heterogeneity [12] to produce a modular toolkit for constructing legged robots.

When considering the trade-off between specially made devices and general-purpose devices of greater complexity, a tipping point appears when it can be shown that general-purpose devices achieve similar quantitative performance metrics to those of the special-purpose devices. In our work, we show that for the task of efficient locomotion on land, water and air, while both carrying payload and producing wireless video reconnaissance, we can use a combination of modular architecture and low cost, low weight, low volume passive body parts to achieve performance competitive with custom devices made to move in each domain. Other systems, with some in the USAR context, that have attempted multiple modes of locomotion, including many amphibious robots [13], [14], [15], [16] as well as flyers that can also have some level of land mobility [17], and some flyers that swim [18], however none that do all three. The proposed system does all three with some manual reconfiguration.

Using a single backpack, the operator may trade-off between the exploratory power of a quadrotor, the long-distance, high-speed, and heavy payload capability of a wheeled vehicle on land, and a boat on water, with only a few minutes reconfiguration. An additional advantage is that all structures are lightweight and cost only a few dollars, making them disposable or easily replaceable. By concentrating versatility in a few multipurpose parts, i.e. the actuator modules, and a multi-use body frame, we achieve a nearly threefold savings of mass and volume compared with three dedicated devices we might have needed to deploy otherwise.

II. Vehicle Design

A. Design Goals

To achieve visibility from arbitrary positions in space (e.g. from flying) or high payload transportation over land and water, while being man-portable, compact, lightweight and low cost, we build one system that alternates between a boat, quadrotor, or car. In other words, we want to maximize

qty	USD each	Item
4	93	Motor Modules
1	40	Central Controller
1	150	UM-6 IMU
1	1.9	Passive Body
4	0.5	Passive Arms
2	1.0	GEMFAN 11x4.7R Propellers
2	1.0	GEMFAN 11x4.7L Propellers
1	1.5	APC 8x8L Propeller
4	0.4	10 cm Tweels
1	0.5	Male-Male Modlock
3	1.0	Securing Straps
1	0.2	Hex Key

TABLE I

INCLUDED PARTS. TOTAL COST: $576.7 USD.

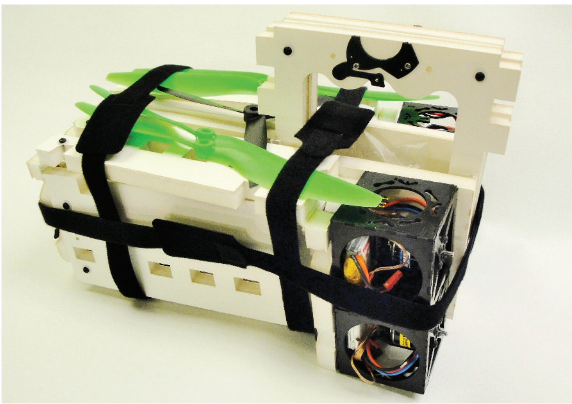

Fig. 1. SEAL Pack in Packed State.

land/sea-crossing payload and flight time while minimizing carrying size, weight, and cost.

The principle design goal reduces to finding part commonality for all three vehicle modes. While it is possible to find one vehicle configuration that simultaneously achieves everything, we have found a system that maximizes our performance metrics by alternating between configurations.

B. SEAL Pack

The final designed SEAL Pack folds into a 1.007 kg, $33 \times 20 \times 14$ cm box plus a handle containing the items in Table I.

1) Active Components: In order to reduce part count, weight, and complexity, a versatile actuator is required. Different types of rotational actuators were reviewed in order to select a motor capable of low and high speed control and position control. Brushed motors are simple to operate, requiring solely a DC voltage. Their classic inrunner design (rotor on the inside of the stator) yields high speed and low torque. Gearboxes are traditionally used if high torque is desired. Brushless motors require a synchronous, alternating voltages to be applied, resulting in a more complicated commutation. They come both as inrunner and outrunner designs, with the outrunners resulting in high torque and low speed. Because of their high torque density, brushless motors are capable of the high speed control required for driving propellers, direct drive torque control of wheels, and direct drive position control for steering assemblies without any modifications between applications. Furthermore, a position sensor is required for position control and a microcontroller is required for closed loop torque and speed control, both of which can be used to commute the brushless motor. Therefore, minimal new hardware is required for a brushless motor, while a gearbox is no longer necessary as it is with a brushed motor.

The actuators were modularized by packaging them with a controller and battery into motor modules. These modules encapsulate the versatility and complexity required of our actuation into identical, easily replaceable parts. Each of the actuator modules is a cubic 6 cm ABS cage with 3 female Modlock connectors[19], and contains an E-Flite Park 400 740 Kv motor, chosen for its high torque constant and small size. A TI TMS320F28035 microcontroller receives motor position feedback from a diametrically aligned magnet mounted to the motor's rotor and an Austria Microsystems AS5145B magnetic encoder and receives motor current feedback from an Allegro Microsystems AC713 Hall effect current sensor. A Thunder Power 350 mAh, 3 cell lithium polymer battery accompanies these components in the module. The combination results in a self contained unit capable of vector control at 100khz with $0.0879°$ accuracy, controlled bi-directional speeds between 0 and 8000+ RPM, bi-directional torque control up to 540 mNm, and attachment times in less than 5 seconds. The SEAL Pack uses four of these modules.

All vehicles include an additional centralized controller module responsible for on-board computation and user and interprocessor communication. The controller, a dsPic30F4011, communicates with a base station computer running MATLAB via a Digi XBee-PRO wireless RF module with up to 45km range. It relays control information to the other active components over CANbus using the Robotics Bus protocol, which is an extension of OpenCAN [20]. The controller interfaces with a CH Robotics UM-6 inertial measurement unit as well.

2) Passive Components: As with the motor, we chose frame materials versatile enough to construct all three types of sea, air, and land vehicles. The vehicle size was determined by the desired payload and obsticle clearances of the vehicles, while maintaining the ability to pack into a single-hand carryable package. The dimensions are seen in Figure 2. All passive components require buoyancy for the boat, high strength for the heavy payloads of the land vehicle, and high strength-to-weight ratios for the air vehicle. Cored composite materials such as carbon fiber balsa core, paper-faced foam board, sealed plastic shells or foam filled structures promise these requirements. We use paper-faced foam board for development due to its low cost and ability to be laser cut; however, a more durable material would be required in the field. Living hinges are created by cutting through one layer of paper plus the foam, leaving a single side's paper, enabling an iterative design approach on component shapes as well as fold locations. For small, heavy use living hinges we applied a high performance filament tape (3M #898) to reinforce the hinge and prevent separation of the paper face from the foam core. Plastic piano hinges were also tested and are an excellent candidate for use with carbon fiber passive components.

Initial design guidelines for the SEAL pack came from [21], of which 19 of the 24 guidelines are used. For the SEAL pack, they evolved into:

- Sharing module functions if functions are closely related
- Modules add functionality when attached differently
- Reusing features/modules without raising part count
- Separate conflicting features to symmetric/opposite edges

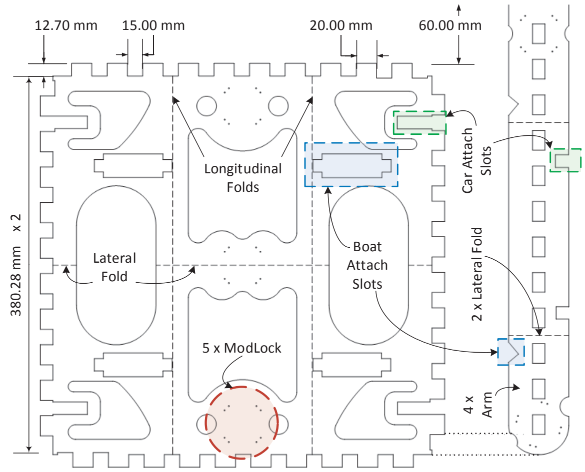

Fig. 2. Passive component plan view with dimensions.

Once the environment for a given task becomes apparent and the user knows which vehicle is required, the user configures the passive components into the appropriate vehicle chassis and adds any vehicle specific components. We use male or female Modlock [19] features made of $1/16$ inch ABS as attachments point for modules and other passive components. In addition, some components are designed for peg-in-slot press-fits and allow us to mate components perpendicularly to each-other.

The SEAL Pack has five frame components: one body and four arms. The body folds in three places; two folds are longitudinal and used to make the sides of the car and boat while the remaining fold is lateral and decreases packing size, giving the prominent handle in the packed configuration. The arms fold in two lateral locations allowing the car to have parallelogram steering when two arms are connected end to end and parallel to each other. The slots on the right of the arms in Figure 2 insert into slots on the body, constraining the body's longitudinal folds to $90\,\mathrm{deg}$ each. Similarly in the boat configuration, the notches on the left of the arms constrain the body's longitudinal folds to $60\,\mathrm{deg}$ when inserted into the rectangular cutouts. When constructing the quadrotor, the pegs on the perimeter of the body insert into the slots on the four arms. The arms prevent the body from folding, while the body prevents the arms from folding.

3) Task Specific Components: The above components can mimic various chassis and powerplants, none of which are useful without being able to apply forces as the context requires. By proper selection of vehicle types, task specific components that react with the external world can be small and simple. For example, a traditional helicopter has one large driving motor with an articulated propeller, a number of small actuators to articulate this propeller, and a smaller tail rotor. The majority of these components are different and specific to this vehicle. On the other hand, a quadrotor has four, identical driving motors yet fills the same vehicle niche. The only task specific attachment for the quadrotor missing from the kit is four, nearly identical, fixed-pitch propellers.

Aside from actuator similarity within vehicles, similarity between vehicles is also desired. For example, a legged land vehicle could consist of a number of identical, high-torque, position controlled rotational actuators, but it would be difficult to reuse actuators or structure for a quadrotor. Instead, it is not a stretch for a four-wheel drive car and a quadrotor to use the same components. In addition, an airboat can consist of a propeller and motor pair like the quadrotor coupled with a motor in low-torque position control, which is similar to low-speed control when driving the car. Airboats have the added benefit of being one of few boat types drivable with a single engine, not requiring a transmission, and not requiring actuated components to contact water.

Static thrust tests of various propellers determined which propellers were best suited to be included in the pack. Testing demonstrated that the GEMFAN 11x4.7 (diameter in inches by inches per thread) propeller is the most efficient slowflyer type propeller for the motor in the active module and thrust required for hovering flight of the quadrotor at 2.2 N of thrust and 17.0 W of power consumption per propeller. Electric or gas type propellers were discarded due to their higher moment of inertia, which is an undesirable trait in RPM controlled rotorcraft like the quadrotor.

The main concern with the airboat is its horizontal shaft mounting and thus the potential collision between the propeller and frame. For this reason, the vehicle has a maximum propeller radius of 10 cm (4 inches). We attempted to correct for the small size with a higher pitch in order to achieve the same thrust. The APC 8x8 electric type propeller is the highest pitch propeller found among electric and slow flyer propellers intended for the low speeds of the boat, which corresponds with the smallest manufacturer-recommended propeller size for the motor of 10x7 when trading size for pitch. The airboat also features a motor shaft mounted Modlock to enable two modules to be mounted together such that one can steer the other via position control.

Because the land vehicle has no suspension, we model the wheels after *tweels* [22]. The compliant mechanism of the tweel is laser-cut from 6.3 mm thick ABS sheet stock with 82 mm long (extended), 1.5 mm thick zig-zag spokes angled at $75°$ from the radial direction across a span of 32 mm from rim to hub. This yields a spring constant of 3 N/mm. An outer rim diameter of 100 mm gives ample ground clearance for the 60 mm cube cage of the attached active module. Tweels with 200 mm were also built for a 70 mm frame clearance. These wheels were not tested for efficiency.

We outfitted a Modlock connector to a DS-503USB 5.8GHz wireless camera. The user can mount the camera in various locations on the vehicle for first-person view (FPV) vehicle control and as a surveillance demonstrator with a usable range of up to 100m.

III. Vehicle Performance

Simply having three modes of locomotion is not useful if those modes of locomotion do not provide value. Each mode of locomotion has a different measure of performance. Non hovering vehicles designed to travel significant distances, such as the boat and car, are measured by average specific resistance, which is described in Equation 1. Flying vehicles are measured by power with respect to mass. We will treat the range metric as endurance. The importance of the speed metric is vehicle dependent and is discussed below.

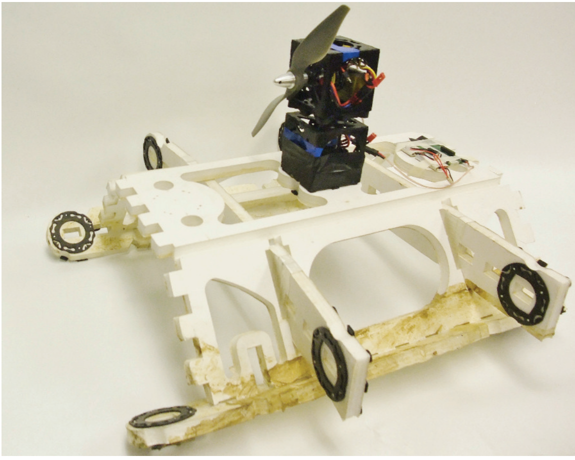

Fig. 3. SEAL Pack in Boat State.

Value	Unit	No Ld
Mass	g	554
Speed	m/s	0.57
Power	W	17
Range	m	470
Total f_{sr}	-	5.5

TABLE II
SEA PERFORMANCE.

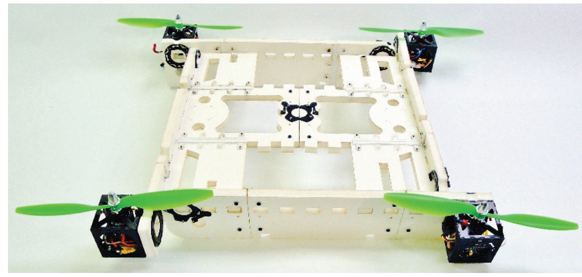

Fig. 4. SEAL Pack in Quadrotor State.

Specific resistance is a dimensionless efficiency metric designed to abstract the vehicle's mass and velocity, making comparisons between vastly different vehicles possible [23]. Using this metric, we can determine if the SEAL pack, either through frame design or actuator choice, has reduced efficiency compared to similar vehicles. If so, the specific resistance will be notably higher. It can be derived using:

$$f_{sr} = P_{av}/mgv_{av} \tag{1}$$

where P_{av} is the average power consumption, m is the vehicle mass, g is gravity, and v_{av} is the average speed.

It is also worth noting that the power consumption includes computation. The controller boards regulate voltage with linear regulators, resulting in a large power consumption of 1.89 W per module. Controller power consumption could easily be reduced by 70% by moving to switching regulators and further by using lower power microcontrollers. A new version with these improvements is in development.

A. Sea Vehicle

The sea vehicle (Figure 3) unpacks from the packed state (Figure 1) in less than 3.5 minutes by an experienced user. Once unpacked, it can travel up to 0.5 km at 0.57 m/s or loiter up to 140 minutes. During testing, the airboat traversed multiple trials of a 14.3m distance over two runs in opposite directions. All tests were done outdoors in a man-made pond to mimic real world scenarios.

The results from testing are summarized in Table II. We directly measured mass, speed, and power consumption. The range is calculated by the average power, speed, and the rated battery capacity. Specific resistance is calculated using Equation 1.

The range is lower and specific resistance is higher than expected, meaning the power is higher than desired. Specific resistances of full size boats range between 2.5 for a Boston Whaler 150 Montauk small fishing boat to 0.001 for super tankers [24], owing their efficiency to the properties of scaling. In search of lower power consumption, further static thrust tests for 8-inch (20.3cm) propellers show a 3.7 W decrease for the same thrust using an 8x3.8 APC slow flyer propeller. Static thrust tests are generally poor measures of thrust and power when the vehicle is not static. At the vehicle test speed of 0.57 m/s the inflow causes an angle of attack change of $0.9°$. When compared to the propellers' angles of attacks of 8.6 for the 8x3.8 and 17.7 for the 8x8 in static air, the error is small enough to assume a lower pitch propeller is ideal. The use of this propeller results in a theoretical $f_{sr} = 4.35$, which still remains high. Another cause of inefficiency could be the boat's propulsion setup and center of mass relative to the center of buoyancy. When attempting higher speeds, the increased thrust on the propeller creates a nose down moment and subsequent submarining. For this reason, the listed airboat's speed is the maximum speed. A redesign by shifting buoyancy to the bow or center of mass to the aft could allow for increased speed or decreased drag. When comparing this design to other swift water swimmers from the robot ontology, such as the Clearpath Kingfisher, the SEAL Pack's battery life at cruise and max speed is roughly $1/3$, and has a comparable loiter time, while being over 50 times lighter [25].

B. Air Vehicle

The air vehicle (Figure 4) unpacks from the packed state (Figure 1) in less than 3.7 minutes. The primary capability that flying brings over the other locomotion modes is mobility over any terrain, easily flying above tree-tops and buildings at over 6.5m/s. The hover endurance, tested in a Vicon motion capture system for position feedback, is shown in Table III ranging from 5.9 to 7.1 minutes depending on payload. The endurance is calculated using average power and rated battery capacity.

Although the quadrotor endurance is lower than many of its size, it is on par in terms of power to weight ratio. Normalizing the measured data using:

$$PtW = \frac{C}{mt} = \frac{P}{m} \tag{2}$$

where PtW is the power to weight ratio in W/kg, C is the battery capacity in Joules, m is mass in kg, t is endurance time in seconds, and P is the power consumption. The SEAL Pack quadrotor gives a PtW of 140 W/kg, while the microdrones md4-1000, touted for its 70 minute endurance, has a power to weight ratio of 100, which is only 29 % better [26]. On the

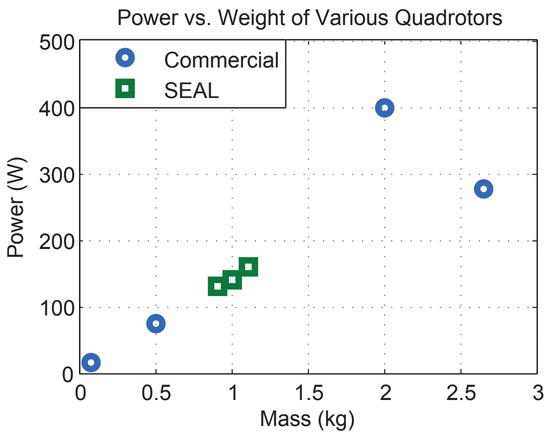

Fig. 5. Power to weight ratios of the SEAL Pack at different loads and other commercial quadrotors; shown from left to right: KMel NanoQuad, AscTec Hummingbird, AscTec Pelican, and microdrones md4-1000.

Value	Unit	No Ld	100g Ld	200g Ld
Mass	g	913	1.009	1111
Power	W	130	140	160
Endurance	min	7.1	6.9	5.9

TABLE III
AIR PERFORMANCE.

other hand, the SEAL Pack has a better power to weight ratio than an AscTec Pelican by 43% [27]. More power to weight comparisons are given in Figure 5. This translates to the lack of endurance being a result of onboard battery capacity in the modules and not a fault of the frame. As a comparison, the AscTec Hummingbird has half the mass, but 1.5 times the battery capacity of the SEAL pack, resulting in an 18.6 minute life. The Hummingbird also has the same payload as the SEAL Pack in quadrotor mode, giving a comparison for both categories that it fulfills in the robot ontology.

C. Land Vehicle

The land vehicle (Figure 6) unpacks from the packed state (Figure 1) in less than 4 minutes. It can travel 8 km with a camera payload, or 5.4 km with an additional 0.5 kg payload. The maximum measured speed achieved with the car is 3.1 m/s. It has driven both outdoors and indoors, traversing grass, ramps, standard and brick sidewalks, and over door thresholds. Distance tests are performed for two laps on a the University of Pennsylvania's 400 m Rekortan track.

The land vehicle's performance shown in Table IV exceeded expectations, despite its underdamped steering and motors operating out of their peak efficiency range. The passive steering linkage reduces slip, but also induces oscillations in steering. Nonetheless, the vehicle navigates terrain and large distances in FPV and third person view. The resulting specific resistance of $f_{sr} = 0.84$ unloaded compares favorably to a RC toy, Traxxas #58064 of similar size, which has a $f_{sr} = 0.86$ and range of 4.5 km when tested under identical conditions. For ground wide area survey robots, range is a key feature, and the SEAL Pack out performs the Traxxas considerably.

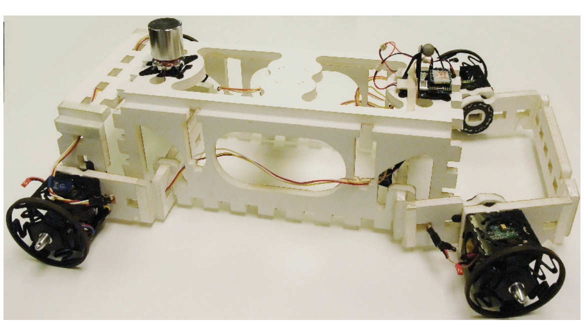

Fig. 6. SEAL Pack in Car State with Payload.

Value	Unit	No Ld	500g Ld
Range	m	8000	5400
Speed	m/s	2.1	1.3
Mass	g	956	1452
Power	W	17	16
Total f_{sr}	-	0.84	0.83

TABLE IV
LAND PERFORMANCE.

IV. Discussion

From the Robotic USAR ontology, the #9 Aerial: Rooftop Payload Drop and the #10 Aerial: Ledge Access tasks are capabilities for the quad rotor configuration. Rooptop and ledge access was demonstrated on the roofs of buildings on the Penn campus. Although explicit payload drop and rigid grasping perch mechanisms were not a design focus for the current implementation, simple passive features in the frame can be used. The payload would include payloads of under 200g which could be small micro robots, self-contained cameras, gas, and other sensors, radio repeaters, or hooks and tethers to enable other robots to gain access to roof tops. For reference, a Gumstix Overo computer, digital camera, Digi XTend 64km radio, and CO_2 sensor are roughly 20g each.

For the #3 Ground: Non-collapsed structure-wide area survey task, the 5 to 8 km path range could be used in scenarios such as surveying building complexes (indoor or outdoor), though would not be well suited for coverage over larger areas. The largest area this path could encircle would be approximately 5 sq. km.

For the #13 Aquatic: Swift Water Surface Swimmer, the path length was significantly less than the ground configuration. In addition, water and wind currents can have much larger effects on this performance. The average speed tested was 0.57m/s which is an indication of the maximum current this mode could handle as well. For tasks such as those used for visualizing piers and sea walls, the range of 470 m might be adequate as the vehicle could be deployed on site with traversal needed only for different views of the structures typically much smaller than 470 m.

Having a system that can be reconfigured to achieve three vastly different modes of locomotion needs to be compared with two other approaches: three separate vehicles - one for each mode that each achieves the performance metrics, or one vehicle capable of achieving all performance metrics by itself.

For the latter case, a flying vehicle is the only robot that approaches having all of the capabilities of the SEAL Pack. It would have to carry 500g for 140 minutes, travel over 8 km, and pack into a $33 \times 20 \times 14$ cm box that weighs 1kg. There are small quadrotors that fit some of the constraints, but none that fit all. For example, the Ascending Technologies Pelican can be packaged into that size as disassembled. It can carry

500g and weighs 650g, however it can only fly for 15 minutes, and reassembly would be much longer than the 5 minutes for SEAL pack. Also, costs are significantly higher for the Pelican.

For the three separate vehicles case, one might consider dividing up the $33 \times 20 \times 14$ cm volume for a boat, flyer, and car, with each having $11 \times 20 \times 14$ cm. This could be achieved with a Kmel NanoQuad flyer, a Lego Mindstorms mobile base, and a small radio controlled boat. While tests have not been done explicitly, it is reasonable to expect that performance of this flyer will not have the payload capabilities of the SEAL pack quadrotor. The mobile base is unlikely to be able to traverse similar terrain simply because its wheelbase is less than 1/3 that of the SEAL pack car, and the payload of the boat will be smaller than the SEAL pack boat again because the vehicle volume is smaller.

V. Conclusions

The presented system is not field-grade, and there are aspects of its design and implementation that can be improved. For example, although the foam core we used is very low cost and has a high strength to weight ratio, its fatigue life is short, the foam tends to crumble away and the paper kinks. Future work should include finding better material for resisting environmental damage, producing water-tight field-grade actuators, and improving power storage capacity. Despite these limitations, our system clearly achieved its stated goal to demonstrate the feasibility of a compact vehicle capable of land, air, and sea locomotion.

Through the employment of multipurpose modular actuators, the use of versatile mechanical parts and the judicious choice of task specific parts, we dramatically improved the mass and volume density of remote-controlled vehicles that would be available to a reconnaissance mission. The vehicles obtained are competitive with commercial products in their size class, and have thus shown that the approach we propose incurs no significant performance penalty, while introducing substantial advantages. We believe further work in this direction would show many more dramatic improvements.

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