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Omnibot: A Small Versatile Robotic Platform Capable of Air, Ground, and Underwater Operation

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***Abstract*— Autonomous systems are increasingly sought after to carry out complex tasks yet most available systems are designed to operate in a limited environment. By combining different mechanisms into a single design, a new kind of universal robotic platform called the Omnibot is proposed, which can fly, move on the ground, move on the surface, and dive into the water at the same time. To achieve this goal, a quadrotor configuration, screwdrive drivetrain, and a bladder-based buoyancy unit are proposed as a robotic design and a proof-of-concept platform is developed. Preliminary results demonstrate that the system is lightweight, cost-effective, versatile, and able to operate in the four kinds of environments and switch between them seamlessly without changing its hardware. The proposed design would enable a robotic system to switch among its methods for locomotion and choose the best mode according to the current goal, environment, and the internal power supply conditions, thus making it especially suited to carry out complex missions in changing and unpredictable environments.**

I. Introduction

Autonomous systems, or unmanned vehicles, have become a very hot topic, many of which, such as Waymo [1], the Google self-driving car, DJI drones [2] and many others, have appeared as major technology drivers and are household names. It is expected that these automatons will help humans by executing dull, dirty, or dangerous jobs in challenging environments instead.

In the past few decades, specialized robotic platforms adapted to different environments constitute the mainstream of robotics research and many of them have found wide applications in various areas. For example, unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs) have become very popular and are being intensively developed and deployed for numerous civil and military applications, most of which are used to survey or monitor different zones. One common feature of such kinds of autonomous systems is that each of them is designed to work in only one type of environment. In other words, it is not expected that a UGV can enter water, nor could a UUV/USV move on the ground.

On the other hand, a handful of systems that can perform tasks in two or three kinds of regions have emerged, making them especially suitable to carry out more complex tasks in varying environments. However, none of them could cover all four common kinds of territories including land, air, water surface, and under water.

In this paper, we propose a small robotic platform, called the Omnibot, that could operate in these four diverse environments without changing its hardware and software. As can be seen from Figure 1, it is built upon multiple available and novel technologies including quadrotor propulsion, screwdrive propulsion, and a buoyancy control mechanism.

In the following sections, we will firstly give a review of the related work that has been done in the field of mobile robotic vehicle design in Section II. Then we describe the design of the Omnibot in detail in Section III. After that, we then illustrate some of the experiments we have done and related results we have obtained in Section IV. Finally, we talk about our conclusions and the future work we plan to do in Section V.

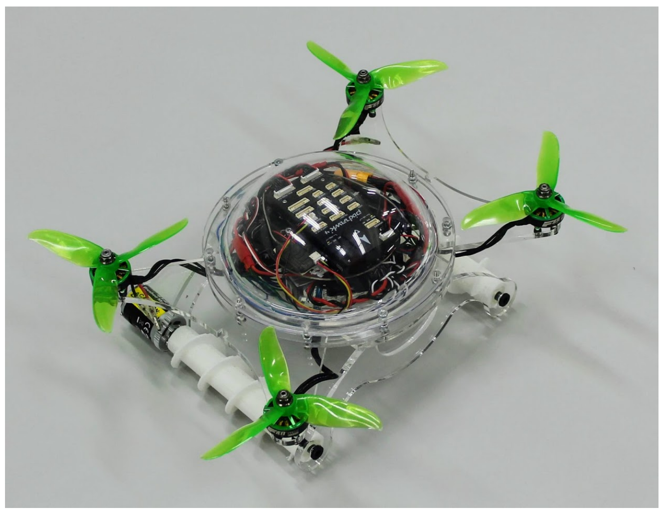

Fig. 1: The Omnibot robotic platform.

II. Related Work

Nowadays, various kinds of autonomous systems are being intensively developed and deployed to numerous civil and military application areas. According to their active regions, they can be divided into two groups, specialized robotic platforms including UGVs, UAVs, USVs, and UUVs, and multi-purpose or cross-domain vehicles, which are composed of vehicles that can cover more than one domain.

A. Specialized Robotic Platforms

In this case, each platform is supposed to be able to operate in one kind of environment only.

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1) UAVs: UAVs mainly cover the air. Also known as drones and originated from military applications, they have now found wide applications in commercial, scientific, recreational, agriculture, and many other areas. In terms of flight modes, UAVs can be roughly divided into three groups: fixed wing, multicopters, and combinations of the first two. UAVs can cover a large area in a short period of time. However, their flight time is restricted by the battery capacity, and their remote sensing data is limited in terms of resolution.

Figure 2 shows a fixed wing plane and a multicopter model.

(a) A fixed wing plane [3]. (b) A DJI multicopter [2].

Fig. 2: Two kinds of UAVs.

2) UGVs: UGVs operate while in contact with the ground. Therefore, they can gather information at a much higher resolution than UAVs. Nonetheless, UGVs are usually much slower in terms of speed and efficiency. Furthermore, they are constrained by whatever obstacles may be present in their environment.

3) USVs: USVs can float on the water, monitor the water surface, and even look into the water in a limited fashion. They are valuable for oceanography due to their low cost and flexibility compared with other means.

Figure 4 shows a model of USV for aquatic observation applications.

4) UUVs: UUVs are targeted for underwater applications, including seabed surveillance, fish and current monitoring, etc. Nonetheless, they may suffer from communication and power supply issues. Typically these platforms are either tethered or prohibitively expensive due to the sensors required for localization in a GPS-denied environment. Furthermore, these expensive platforms generally require a larger vessel to transport, deploy, and retrieve, adding to overall costs.

Fig. 3: UGVs used for military purposes (courtesy of [4]).

Fig. 4: A USV model (courtesy of [5]).

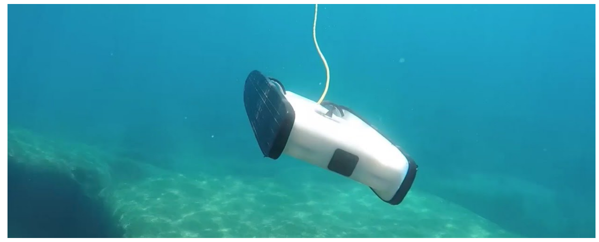

Fig. 5: A UUV model (courtesy of [6]).

Figure 5 shows a UUV model for underwater aquatic observation applications.

B. Multi-purpose Robotic Platforms

On the other hand, some types of multi-purpose systems have also been proposed, most of which can enter two kinds of regions while few can operate in three environments.

As a matter of fact, robots that can cover two kinds of regions are not rare. One case in point is that of the hybrid air-water microrobot from Chen et al. [7] which weighs 175 milligrams. This aerial-aquatic microrobot is capable of flapping its wings to propel itself through air and water. The water to air transition is not simple as it has to overcome significant surface force. Moreover, it also has to overcome limitations of flapping wing motion in taking off from the water. The microrobot overcomes this by igniting a small chemical reaction that propels it away from the surface of the water. The Air XAV [8] is another hybrid air-water platform that economizes in weight and complexity by using the same motors for flight as for underwater locomotion. A fixed-wing airplane design and passively flooding/draining wings allow it to obtain neutral buoyancy in water while shedding the excess weight upon water egress using flight for speed and range while its water function affords it stealth and loitering capabilities.

Another example is the AQUA [9], which is a bi-modal amphibious robot that employs flipper-like legs to move from land and into the water. It uses six appendages to propel itself in the water while using a cockroach-like gait when walking on land. The legs are compliant which serves to provide additional terrainability to the robot.

On the miniature robotics side of the spectrum, the Aquapod [10] is an amphibious robot that moves around by effectuating tumbles on land and using a buoyancy control unit (BCU) to ascend and descend in a column of water.

Comparatively, few platforms can navigate through more than two domains. The multi-field universal wheel for the air-land vehicle (MUWA) [11] is unique in that it can navigate in three domains. As we can see from Figure 6, the MUWA

Fig. 6: The MUWA model (courtesy of [11]).

can fly in the air, float on water, and travel on the land at an arbitrary angle using its specially designed features and algorithms.

III. The Design of the Omnibot

By leveraging a new propulsion method for land and water locomotion in conjunction with quad-rotor designs for flight, coupled with a waterproof hull and buoyancy control unit to alter its density, the Omnibot is able to travel on and through water, over land, and in the air. To the authors' knowledge, the Omnibot is the first robot that can cover all four typical kinds of environments.

However, covering all four mentioned domains presents special challenges. As stated, there exist robotic solutions for each or a couple of domains, however, each has requirements or solutions that can be at odds with the requirements of a different domain.

We break these challenges into the locomotive and structural aspects, where the former covers the means by which the Omnibot is to move itself through a given media and the latter covers the physical properties the platform has to deal with the four types of regions.

A. Locomotion

Central to the functionality and usability of a mobile robotic platform are the methods by which it moves itself through the environment it is in. Often, the aforementioned methods amount to be a fundamental choice as they place constraints on battery life, impact path feasibility, as well as the types of traversable terrain, variables which are of critical importance to all mobile platforms with a limited supply of power.

For the Omnibot, the screwdrive powertrain was chosen for its ability to traverse both land and water environments while a quad-rotor design was chosen for flight due to its stability, vertical-take-off-and-lift (VTOL), and hovering capabilities.

1) Screwdrive: Screwdrive propulsion is a relatively neglected method of locomotion that has been shown to successfully propel military, scientific, and recreational vehicles across a wide variety of terrains ranging from snow to water and mud to sand [12], [13], [14]. However, most of this core research dates back to the 1960s and 1970s. A few modern exceptions are [15] and [16], where the former explores multi-screw drives and the latter the modeling of a dual screw system. However, in the robotics community they are exceptional as screwdrives are by no means a popular form of locomotion.

On the Omnibot, a dual-parallel screw configuration is chosen as shown in Figure 8. The screws are set up such that they are opposite-handed and are contra-rotated to achieve a net forward displacement, as shown in Figure 7.The screw itself consists of a cylinder with one or more blades wrapped in a helix around its exterior. On a system with more than one screw, the screws can be actuated to achieve omnidirectionality.

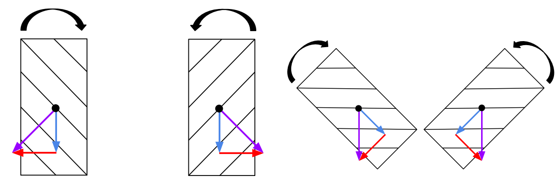

Fig. 7: Screwdrive forces on a penetrable terrain: rolling forces are in red, tractive in blue.

The propulsion by the screws depends on many factors, however, the penetrability of the terrain is one of the most important ones since this determines the interplay between tractive and rolling forces. *Rolling forces* result from the rotation of the cylinder about its axis and are similar to those generated by a car's wheels.

Tractive forces, as they have been called by Freeberg [15], are the defining characteristic of screwdrives. As the screw rotates, the blade displaces the medium along its longitudinal axis creating propulsion.

If the blade cannot penetrate a terrain, rolling forces dominate. In soft terrains, such as sand, mud, and snow, a combination of rolling and tractive forces play a role, although typically tractive forces are greater. Finally, in water or like fluids, tractive forces dominate and rolling forces are negligible.

In systems with two independently actuated screws, the inter-screw angle also affects the resulting motions from the net forces of the competing or cooperating screws as can be seen in Figure 7. For parallel screws, the resulting motion can be expressed by:

$$\begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} = \frac{R}{2L} \begin{bmatrix} -L & L \\ L & L \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \omega_{M1} \\ \omega_{M2} \end{bmatrix}$$

where V_x,V_y, and ω are the resultant velocity components, ω_{M1} and ω_{M2} are the motor speeds, R is the effective radius of the screw, and L is the distance between the screws.

2) Thrusters: A quad-copter design was chosen based on its ability to provide the amount of thrust necessary to lift the platform, its ability to offer VTOL, but most importantly because it allows effective air to ground and water transitions and vice versa, without impeding the other modes or transitions. This design uses the T-Motor F40 Pro II KV2400 motors which weigh 29.5 grams a piece, yet are able to provide a theoretical maximum 1400 grams of thrust when at full throttle and paired with a 4 cell Lithium Polymer battery.

The VTOL capabilities and controllable nature allow the robot to land carefully atop the screwdrive subsystem. Similarly, when transitioning from water to air, the Omnibot was designed in such a way that the propellers are located at the top of the robot. Fixed-wing alternatives would have placed additional and incompatible restrictions on weight, size, and other variables all while increasing the size.

B. Mechanical Design

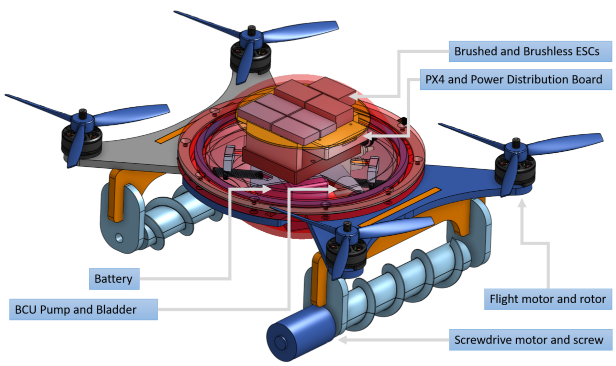

Fig. 8: Omnibot CAD Rendering.

Most of the Omnibot's electronic parts are enclosed in an extruded acrylic transparent sphere, this facilitates decreased drag both on land and in water. The transparency of the enclosure allows for cameras to be added inside without any particular accommodations.

The enclosure sphere is connected to the flight motors via a set of independent wings that are bolted to the sphere using the same bolting pattern that seals the two hemispheres. These motors are located at the extremities of the wings and are designed such that the DALPROP 4045 tri-blade propellers are sufficiently far away from the robot to avoid collision during flight, but also to allow simple access to the shell.

The robot itself has a ground clearance of 1.1 inches, which is helpful for land navigation purposes, by virtue of the screwdrive system. Each screwdrive ”leg” is press fit and acrylic welded orthogonal but in a parallel direction to each wing. The motors that power the screws bolt on to the legs for ease of access and maintenance.

A removable payload “disc” around the globe can be used to extend the capabilities of the robot in various important ways. Different sensor suites will be mounted on the disk in such a way to allow easy deployment of many Omnibots with different payloads.

1) Weight and Cost: By integrating multiple mechanisms together, we have built a prototype, the weight of which is 1,418 grams, with a cost less than $1,000 USD. Therefore, it is cost-effective to deploy in different environments to test its capabilities.

2) Density: The buoyancy control unit works by ingesting water, such as the Aquapod [17], and altering the robot's mass. Since the bladder is contained within a fixed volume, the density changes:

$$\rho_{omnibot} = \frac{(omnibot_{mass} + bladder_{mass})}{omnibot_{volume}}.$$

In a fluid, the interplay of the robot's weight versus its buoyancy determines whether it floats or sinks per Archimedes' Principle. To engage in a dive, the robot must ingest water to the point where the weight of the robot becomes greater than the weight of the water it is displacing. For this purpose, a peristaltic pump is employed. And the Omnibot just needs to reverse the pump's direction to ascend.

The Omnibot weighs approximately 1,418 grams dry and with an empty bladder and its volume is designed such that the robot is 25 grams over the neutral buoyancy point, therefore, within the bladder's water capacity.

3) Sealing: The main seal of the Omnibot consists of a face type seal employed between the two flanged hemispheres that comprise the main body of the robot. The hull halves squeeze an O-ring that is contained within a gland. This O-ring together with the gland provide protection for more than the equivalent of 5 meters of internal and external pressure.

The numerous connections for the thrusters and screwdrive motors on the exterior of the robot are made through cable penetrators which also employ an elastomer to seal the interface where the surface is breached while allowing cables through. These are fastened by a threaded rod and nut, which facilitates removal for field maintenance.

C. Electronics and Software

The prototype is built by integrating many off-the-shelf parts together with custom-designed components. In terms of the electronic subsystem, lightweight yet powerful T-Motor F40 Pro II brushless motors together with their corresponding F35A electronic speed controllers (ESCs) were chosen for flight propulsion. The Pixhawk 4 flight controller [18] together with the PX4 flight stack [19] were chosen for their versatility and configurability. This serves as the starting point from which software modifications were made in order to add ground and water modes in addition to the existing aerial options.

The PX4 is built upon the classical proportional, integral, derivative (PID) controllers, as shown in Figure 10, for vehicle control. The controllers are implemented in three layers, passing results from the highest-level controller, i.e., the velocity & position controller, to the lower-level controller, which is the attitude controller, and then from there to the lowest level, the rate controller. The P, I and D coefficients used in our design are listed in Table I.

Backed by simple PID algorithms, the system is able to cover the modes of an UAV, UGV, USV, and UUV, driving one of the two distinctive propelling mechanisms according to the current situation of the environment and allocated goal.

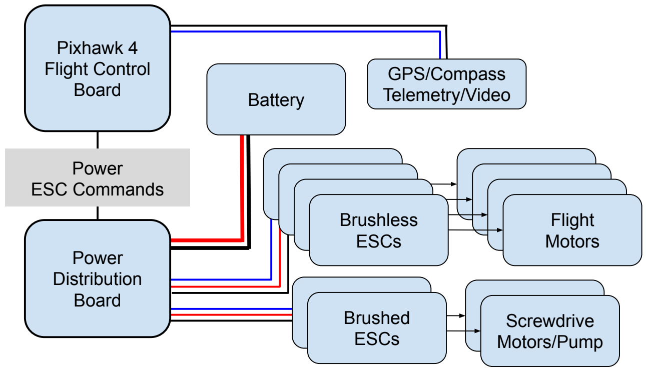

Fig. 9: Omnibot Electronic System Schematic.

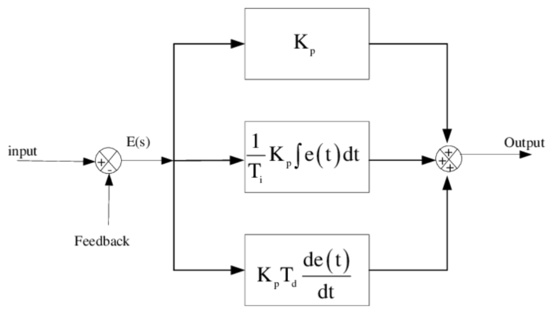

Fig. 10: The diagram of a PID controller [20].

Layered Controllers	States	P	I	D
Velocity & Position	XY	0.95		
	Z	1.0		
	XY velocity	0.09	0.02	0.01
	Z velocity	0.2	0.1	0
Attitude	Pitch	6.5		
	Roll	6.5		
	Yaw	2.8		
Rate	Pitch rate	0.15	0.2	0.03
	Roll rate	0.15	0.2	0.003
	Yaw rate	0.2	0.1	0

TABLE I: The PID coefficients used in our system.

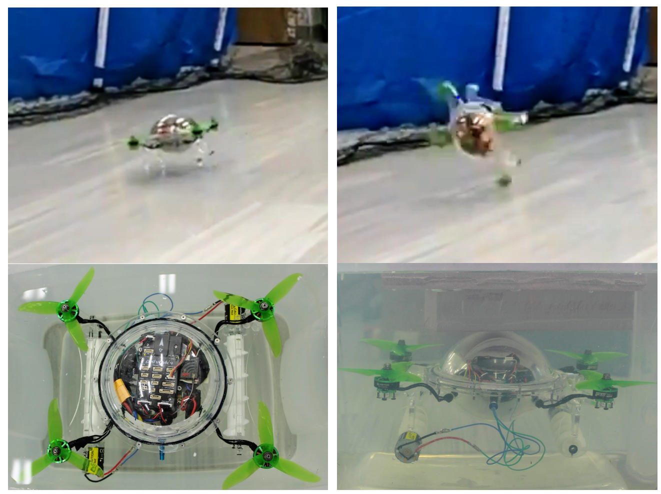

Fig. 11: Clockwise from top left: preliminary flight, submersion, and water surface testing.

IV. Experiments and Results

A. Laboratory Tests

The proof-of-concept model was first tested in each individual environment as shown in Figure 11.

The first tests involved testing the water-worthiness of the robot. The robot was subjected to bidirectional pressure gradients in order to stress test the main seal as well as the ports' seals. Internal pressure testing was done utilizing a compressed air line and visually verifying no air escaped while submerged in a container. The external pressure test was performed in a similar manner but with pressure provided by hydrostatic water pressure and visually inspecting for water within the clear shell.

Land locomotion was verified in a lab environment on relatively flat but roughly textured floors. The objective was to engage the screwdrive system and verify that the movement speed was controllable and adequate. As expected, in an impenetrable terrain of relatively high friction, the screws act like rollers with no tractive effort.

Lastly, we verified air function within a controlled and netted environment. The goal here was to use the remote control to power the robot off the ground. This was successful with the robot lifting and pitching forward. There is more work to be done in this area, however, the motors are indeed capable of lifting the robot.

B. Outdoor Tests

After indoor testing of the Omnibot in each individual environment, testing in a real-world setting at the docks of the University of Minnesota Boathouse on the Mississippi River was planned. At the time of the experiments river ice was common around the dock and there was a section of floating ice trapped next to the docks that served as a convenient platform for launching the Omnibot (Figure 12b).

The outdoor experiments consisted primarily of water navigation, locomotion on ice, and the transition from the floating ice shelf into the water to verify functionality. The first experiment was carried out by sealing the robot, arming the system, manually placing the robot in the water and moving about using the screwdrive system (Figure 12a). Next the robot was again manually placed on the floating ice manually maneuvered in a circle, staying on the ice. Lastly, a land to water transition was carried out by driving the robot off the ice and into the cold Mississippi water (Figure 12c).

The outdoor experiments were carried out at approximately 27 degrees Farenheit, although the water temperature was not measured, it was as cold, if not colder. This was significant due to the elastomeric nature of the seals, which can shrink and become brittle under low temperatures. The experiments were successful in that they functioned as was expected, with the screwdrive system successfully moving the robot in the water, on the ice, and during the launch. To note was the efficacy of the screwdrive system on ice. Unlike other impenetrable terrains which limit the screwdrive system in terms of forward locomotion, locomotion on ice proved

(a) Water operation in the Mississippi River.
(b) Omnibot resting on floating ice.
(c) Ice to water transition.

Fig. 12: Outdoor Omnibot prototype testing on the Mississippi River.

to have a forward component and the resulting motion was faster than even when in water. This is likely due to the low friction between the ice and the screws allowing the robot to "skate" on ice.

Please see the associated video for more details.

V. Conclusions and Future Work

To further advance the competence of robotic platforms in diversified scenarios, we proposed a new platform that can cover the four common environments that a robot may encounter (land, water, air, and underwater), making it possible to operate in unforeseeable and unstructured terrains.

Upon building a prototype, we tested it in different kinds of terrains as well as its ability to transition seamlessly among distinct modes. Experimental results demonstrate that the Omnibot proof-of-concept is able to travel through all four kinds of environments as expected.

The Omnibot can serve as a common platform for a varied mission set. Outdoor aerial and underwater operation were outside the scope of this endeavor but are planned for future experiments. In the near future, we plan to expand the Omnibot's capabilities by equipping it with sensors for specific applications, such as crop monitoring via land and air, lake health evaluation from the air, surface, and in the water, search and rescue missions, among others.

VI. Acknowledgements

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References

[1] "A new way forward for mobility." [Online]. Available: https://waymo.com/redirect/
[2] "DJI - The Future Of Possible." [Online]. Available: https://www.dji.com
[3] J. Falconer, "Fixed-Wing UAV | Aerial Data Systems." [Online]. Available: http://uaspi.com/fixed-wing/
[4] "UGV, applications and functions for professional use," Jan. 2016. [Online]. Available: https://www.embention.com/en/news/ugv-professional-use-applications-functions/
[5] "CYBERJET 185 - Usv by TECDRON | DirectIndustry." [Online]. Available: http://www.directindustry.com/prod/tecdron/product-117421-1226113.html
[6] OpenROV, "Trident Underwater Drone." [Online]. Available: https://www.openrov.com/
[7] Y. Chen, H. Wang, E. F. Helbling, N. T. Jafferis, R. Zufferey, A. Ong, K. Ma, N. Gravish, P. Chirarattananon, M. Kovac, and R. J. Wood, "A biologically inspired , flapping-wing , hybrid aerial-aquatic microrobot," vol. 5619, no. October, pp. 1–12, 2017.
[8] W. Weisler, W. Stewart, M. B. Anderson, K. J. Peters, A. Gopalarathnam, and M. Bryant, "Testing and characterization of a fixed wing cross-domain unmanned vehicle operating in aerial and underwater environments," *IEEE Journal of Oceanic Engineering*, vol. 43, no. 4, pp. 969–982, 2018.
[9] G. Dudek, P. Giguere, C. Prahacs, S. Saunderson, J. Sattar, L. A. Torres-Mendez, M. Jenkin, A. German, A. Hogue, A. Ripsman, J. Zacher, E. Milios, H. Liu, P. Zhang, M. Buehler, and C. Georgiades, "AQUA: An amphibious autonomous robot," *Computer*, vol. 40, no. 1, pp. 46–53, 2007.
[10] S. Dhull, D. Canelon, A. Kottas, J. Dancs, A. Carlson, and N. Papanikolopoulos, "Aquapod: A small amphibious robot with sampling capabilities," in *IEEE International Conference on Intelligent Robots and Systems*, 2012, pp. 100–105.
[11] K. Kawasaki, M. Zhao, K. Okada, and M. Inaba, "Muwa: Multi-field universal wheel for air-land vehicle with quad variable-pitch propellers," in *IEEE International Conference on Intelligent Robots and Systems*, 2013, pp. 1880–1885.
[12] W. W. Fales, D. D. Amick, and B. B. Schreiner, "The Riverine Utility Craft (RUC)," *Journal of Terramechanics*, vol. 8, no. 3, pp. 23–38, 1972.
[13] B. Cole, "Inquiry into amphibious screw traction," *Proceedings of the Institution of Mechanical Engineers*, 1961.
[14] H. Dugoff and I. R. Ehlich, "Model tests of bouyant screw rotor configurations," *Journal of Terramechanics*, 1967.
[15] J. T. Freeberg, "A Study of Omnidirectional Quad-Screw-Drive Configurations for All-Terrain Locomotion," Ph.D. dissertation, 2010.
[16] D. Osiński and K. Szykiedans, "Simulation Model of Small Screw-Propelled Vehicle," *Machine Dynamics Research*, vol. 38, no. 4, pp. 43–49, 2014.
[17] A. Carlson, "Aquapod : The Design of Small Amphibious Tumbling Robot," Ph.D. dissertation, 2012.
[18] PixhawkAdmin, "Introducing Pixhawk® 4 - the flight controller for developers," Jun. 2018. [Online]. Available: https://pixhawk.org/pixhawk4/
[19] "Open Source for Drones." [Online]. Available: http://px4.io/
[20] L. Dwi, S. Herlambang, and R. D. Muhammad, "Optimization pitch angle controller of rocket system using improved differential evolution algorithm," *International Journal of Advances in Intelligent Informatics*, vol. 3, no. 1, pp. 27–34, 2017.