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PROPAGATOR 2: A PLANING AUTONOMOUS SURFACE VEHICLE WITH AZIMUTH RIM-DRIVEN THRUSTERS

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ABSTRACT

This paper outlines the research and testing that went into the mechanical design and implementation of PropaGator 2. The goal of this project was to develop a small-scale, high-speed, fully autonomous surface vehicle (ASV). For the purposes of this paper, small-scale is defined as displacing less than 100 lbf of water, while high-speed is defined as greater than 10 kts. In particular, this paper focuses on the design of the ASV's hull, azimuth steering system, Kort nozzle, and rim-driven hubless propellers. There are many applications for such a platform including, search and rescue, reconnaissance, minefield investigation, and small payload transportation between surface vessels.

1. INTRODUCTION

Autonomous vehicles have gained popularity in recent years due to the advancements in technology. The processing capabilities of computers have increased with a concurrent decrease in cost. Sensors that were once uncommon have become more common due to the growth of the hobby robotics market. The autonomous vehicle population at the University of Florida (UF) reflects this growth.

At the UF Machine Intelligence Lab (MIL) students from electrical, mechanical, and computer engineering departments design autonomous vehicles for land, sea, and air. Recently, the lab has placed an emphasis on naval vessels. MIL's first ASV, built in 2012-2013, was PropaGator 1 [1]. PropaGator 1 was designed with the intention of adding a surface vehicle to a heterogeneous robotic swarm [2]. The required capabilities of the ASV were to autonomously navigate an obstacle course in the water and to maneuver in any direction on the water's surface. The ASV also was limited by weight and volume constraints of 120 lbf and 72 in x 36 in x 36 in respectively. These constraints were imposed to allow the boat to be eligible to compete in the 2014 AUVSI Foundation's RoboBoat Competition. Due to the strict time constraint placed on the development of PropaGator 1, priority was placed on the rapid design and construction of the ASV.

It was necessary to further reduce the development time to allow sufficient time for testing. Like all displacement vehicles, PropaGator 1's theoretical maximum velocity was determined by its hull speed. At hull speed, an ASV becomes trapped behind its own bow wave and is no longer able to increase its velocity. Hull speed can be estimated using the following formula [3],

$$v_{hull} \approx 1.34\sqrt{L_{wl}}\ , \qquad (1)$$

where v_{hull} is the hull speed measured in kts and L_{wl} is the length of the waterline measured in ft. Using this formula, the maximum top speed of PropaGator 1 was predicted to be 3.14 kts.

While PropaGator 1 was a fully functional ASV, the vessel's speed and weight limited its ability to complete long range missions. The combination of the drag caused by the hull and weak trolling motors prevented the ASV from navigating the obstacle course in a more timely fashion. Due to the design of the ASV, PropaGator 1 could not be easily modified for improvement. In order to achieve the desired performance, a new platform had to be developed.

PropaGator 2, as shown in Figure 1, was conceived to far exceed the performance of PropaGator 1. Without sacrificing maneuverability, the new ASV was designed to displace less than 100 lbf of water, travel at 10 kts, and still meet the size constraints of its predecessor.

Figure 1. CAD render of PropaGator 2

2. HYDROFOIL RESEARCH

As shown in Equation 1, the maximum speed for displacement vessels is dictated by a single geometric parameter, the length of the water line. Since a constraint of a maximum length of 72 in was imposed, the decision was made to design a displacement hull that featured hydrofoils. Like an aircraft wing, hydrofoils produce lift as the vehicle moves through the water. By partially raising the ASV out of the water, the ASV is allowed to ride over its bow wave and reach velocities greater than those determined by the hull speed. The hydrofoils were designed using an Eppler 817 hydrofoil cross section [4]. An image of the foil shape can be seen in Fig 2.

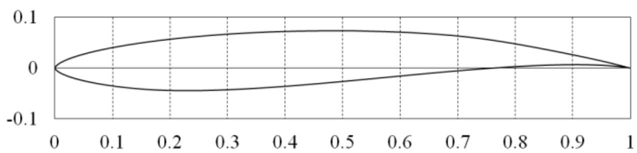

Figure 2. Eppler 817 cross section used to design the hydrofoils tested on the prototype

This cross section was chosen for its minimal disposition towards cavitation and its ease of manufacturing. The foil was cut using a 4-axis CNC mill and tested for its lift and drag characteristics in a wind tunnel shown in Figure 3.

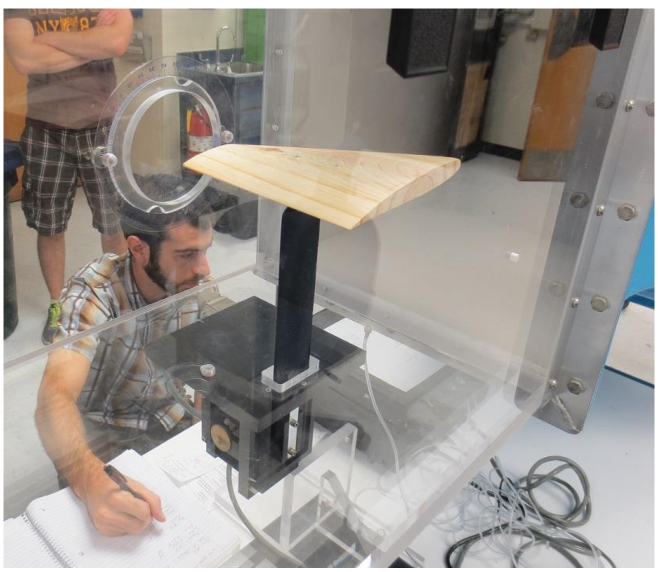

Figure 3. Hydrofoil mounted in the wind tunnel

The goal of the test was to determine the angle of attack that produced the greatest lift-to-drag ratio as well as the maximum lift force that the hydrofoil could generate while moving in the water at 10 kts. The air in the wind tunnel had a Mach number of approximately 0.2, therefore no significant effects due to compressibility were present. Water, under the ASV's normal operating conditions, may also be assumed to be incompressible. Since both fluids were incompressible and the Reynolds number of the ASV's top speed was matched with the wind tunnel's Reynolds number, the data collected in the test estimated that one hydrofoil, with an angle of attack of 5°, could produce 25.62 lbf of lift when the ASV is traveling at 10 kts with a lift-to-drag ratio of 6.55. This would allow a 100 lbf ASV to completely lift out of the water when moving with a velocity of 10 kts.

After the wind tunnel results were analyzed, a wooden prototype hull with hydrofoils was constructed as shown in Figure 4. Two fixed 80 lbf thrust trolling motors were installed onto the prototype and a number of speed tests were conducted in order to determine its maximum velocity. The prototype was able to achieve a speed of 6 kts, nearly twice as fast as it would have been able to move if it didn't have hydrofoils. However, it was not able to generate enough lift to completely rise out of the water. Lift can be calculated with the following equation [5],

$$F_l = \frac{1}{2}\rho v^2 A C_l, \qquad (2)$$

where F_l is the lift force in lbf, ρ is the density of water in lbm/ft^3, v is the velocity of the ASV in ft/s, A is the reference area of the hydrofoil in ft^2, and C_l is the dimensionless coefficient of lift.

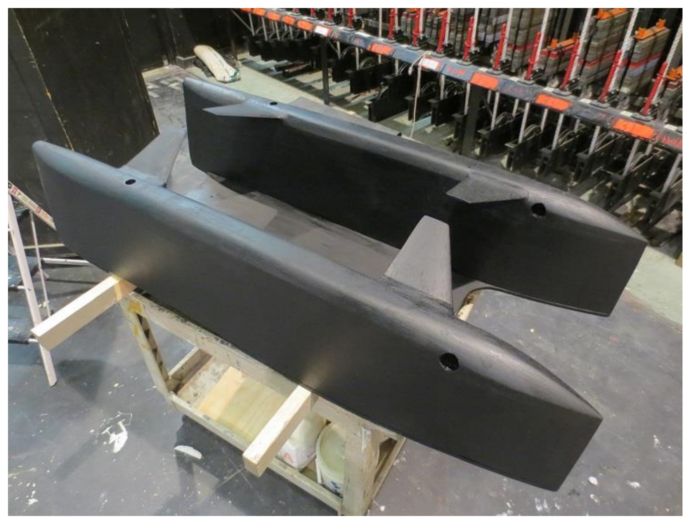

Figure 4. Underside of the wooden prototype hull featuring hydrofoils

The reason why the prototype was unable to completely lift out of the water was due to drag. In order to quantify the amount of drag the prototype generated, it was towed fifteen feet off the port side of a larger boat. A load cell was used to measure the drag force acting on the prototype at a variety of velocities. Additionally, flow simulations were conducted in SolidWorks as another way to estimate the drag force. The results of both the empirical testing as well as the SolidWorks simulations can be seen in Figure 5. In general, the SolidWorks simulations coincided well with the measured values of drag obtained in the drag test. Part of the reason that the SolidWorks values are higher than the empirical data is that SolidWorks did not factor in the reduced drag on the hull as the prototype was lifted out of the water. Even so, SolidWorks provided conservative estimates on drag and lift that helped in the design of our next and final hull.

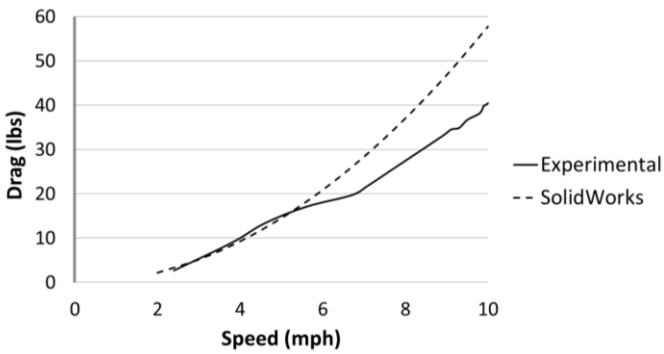

Figure 5. Drag test and simulation results

While the hydrofoils did help lift the prototype out of the water, causing a reduction of drag due to less wetted surface area, the largest contributors of drag came from the motors themselves, a fact that will be explained below. Drag may be calculated with the following equation,

$$F_d = \frac{1}{2}\rho v^2 A C_d, \quad (3)$$

where F_d is the force due the drag in lbf, C_d is the dimensionless coefficient of drag, and ρ, v, and A have the same meanings and units as Equation 2. In this analysis, C_d is assumed to be a function of the Reynolds number. Since drag is a function of v^2, as the prototype increased its velocity, the drag caused by the motors increased with the velocity by a power of two. The decrease in drag caused by the lifting of the prototype was not able to offset the additional drag caused by the motors, thus the overall drag of the prototype was always increasing with velocity. As the velocity was increased, at a certain point, the available thrust produced by the motors became less than the total drag. Therefore the prototype was no longer able to accelerate and gain velocity.

3. HULL DESIGN

After proving that the prototype would never be able to achieve 10 kts, a new hull was designed. The upper half of the hull was modeled after the M80 Stiletto shown in Figure 6. The flat planes that make up the majority of the features on the top half of the ASV are aesthetically pleasing while also being easy to manufacture. The research performed on the prototype with hydrofoils helped motivate many of the design choices used on the submerged portions of the hull. As shown in Equation 1, the length of the waterline constrains the maximum speed a displacement style hull can achieve. However, the maximum velocity of a planing hull does not depend on its length. The maximum speed of a planning vessel can be predicted using Crouch's formula,

$$v_p = \frac{C}{\sqrt{\frac{D}{SHP}}}, \quad (4)$$

where v_p is the maximum planing velocity of the boat measured in kts, C is a constant based on the hull form of the vessel, D is the amount of water the vessel displaces in lbf, and SHP is the shaft horsepower at the propeller. The displacement term is another justification on keeping the weight of the ASV to a minimum. To achieve this low weight, plugs for the ASV's hull were cut out of EPS foam using a CNC mill. The plugs were then conditioned so that a fiberglass mold could be created. Once the molds were finished, the ASV was constructed out of fiberglass. The use of fiberglass gave the ASV structural strength while still being light weight.

Figure 6. U.S. Navy's M80 Stiletto

A catamaran design was chosen over a monohull for several reasons. First, catamarans offer more stability in the roll direction than a traditional monohull. Second, catamarans are also able to displace the same amount of water with a shallower draft compared to a comparable monohull, allowing an ASV to navigate shallow waters safely. Finally, catamarans also typically have the advantage of providing less resistance in the water than a comparably sized monohull [6]. The shallow deadrise helps provide a smooth ride to reduce noise for the on-board sensors while still providing a large planning surface to generate lift [7]. Hard chines were added to the side of the hull to give the ASV better forward tracking. The upper style chines also help redirect the water from riding up the side of the ASV which results in a reduction of drag. The V-shape front of the pontoons is designed to help break waves in choppy waters. Once the water is separated, the pontoons have a constant cross section until the stern of the ASV ends with a hard transom. The hard transom allows the water to separate from the ASV at a known point and helps to prevent issues with flow separation.

4. AZIMUTH STEERING SYSTEM

PropaGator 1 featured four trolling motors that were rotated at set angles of 30° from forward, allowing the ASV three degrees of freedom; translation in two directions and heading. While this configuration can achieve motion in any direction, the ASV loses efficiency since all motions are a result of four thrust vectors with components in opposition. Since the ASV primarily moves forward, it makes sense to design the forward direction to be the most efficient direction for the ASV. By utilizing two azimuth thrusters, PropaGator 2 is able to achieve the same mobility as PropaGator 1's four trolling motors [8]. An azimuth thruster is simply a marine propeller than can be rotated about the vertical axis to assist in steering. By going from four motors to just two steerable motors, the drag caused by the motors was reduced. Additionally, by using steerable motors, PropaGator 2 is more efficient than its predecessor, especially when moving forward and backwards.

5. PROPULSION SYSTEM

The drag test experiments verified that the large trolling motors were the largest contributors towards drag at high speeds. As a result, it was decided to design and manufacture a new propulsion system with no submerged motors. One of two identical thrusters for PropaGator 2 is shown in Figure 7. The goal was to minimize drag by shrinking the water footprint of the propulsion system. Rather than having the motors in the water like the motor pods developed by Hsieh et al. [9] or standard trolling motors, the motors are located inside of the hull. The power is transmitted from the motor to the propeller through a timing belt that is attached to the output shaft of the motor and the rim of the propeller. This rim-driven transmission eliminated any drag caused by the hub of a propeller.

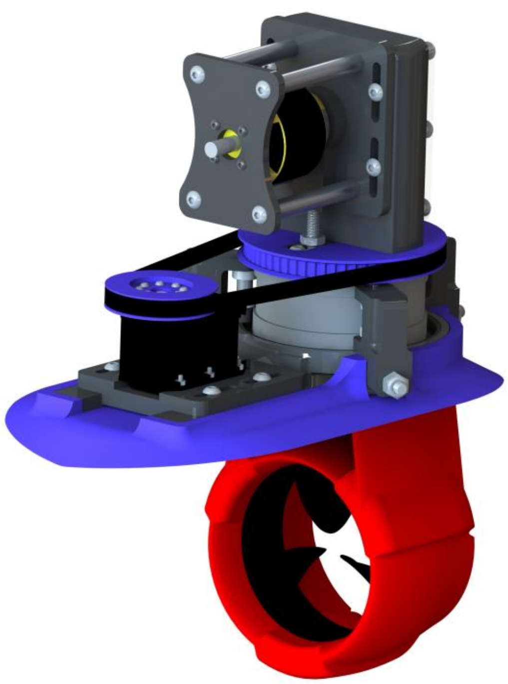

Figure 7. Assembly of PropaGator 2's propulsion system

5.1 KORT NOZZLE

For safety reasons, it was decided that all propellers should be shrouded. Unfortunately, adding a shroud leads to additional drag. By designing a propeller that is enclosed by a duct, also known as a Kort nozzle, it was possible to create a duct that helps generate high thrust at low speeds [10] while still producing minimal drag when moving through the water. Ducted-propellers can also help increase fuel efficiency by allowing the ASV to run the propellers at a lower RPM while still maintaining the same velocity as an equivalent ASV with non-ducted propellers. Furthermore, the ducts prevent prop walk, a phenomena that causes the stern of the boat to strafe in the direction of the propeller's rotation. Typically twin-screw vessels, boats with a propeller on the starboard and port side, will have two different shaped propellers; one that rotates clockwise to achieve forward motion and one that does so by spinning counter-clockwise. The counter-rotating propellers balance out the forces that cause prop walk. However, by using the ducted-propellers, only one type of propeller needs to be manufactured, which allows for easier replacement if one breaks.

5.2 PROPELLER DESIGN

The motivation behind the development of the propulsion system was to reduce drag as much as possible. During simulations and testing, it was determined that the hub in a ducted propeller serves two purposes: to provide strength to the blade roots and to provide an attachment point for the motor. The hub does not produce any thrust, but it does produce drag. By migrating to a rim-driven design, the hub's only remaining purpose was to provide strength to the blades. Unfortunately, the hub only offers strength to the root of the propeller, which in general, experiences loads that are much lower than those experienced by the tips [11]. By inverting the propeller into a hubless configuration as shown in Figure 8, the moment arm acting on the propeller tips is reduced, causing an overall reduction of bending moment on the rim-driven propeller compared to an equivalent standard hub-driven one. By eliminating the hub, the drag that it produces is eliminated. The hubless propeller also has the advantage of being resistant to propeller fouling due to debris [12].

The propeller blades themselves were designed using Crouch's Method [13]. The maximum planing speed of the ASV was calculated using Equation 4. The required pitch to obtain that speed can then be found using,

$$p = \frac{1215.22 \cdot v_p}{.9 \cdot RPM}, \tag{5}$$

where p is the pitch of the propeller measured in in, RPM is the maximum rotations per minute the motor is capable of spinning, and v_p is calculated in Equation 4. This equation assumes that the operating speed of the boat occurs when the motors are outputting 90% of their total power and speed. The pitch is the theoretical distance that the propeller should move forward with one rotation, like a screw turning through wood. In practice, the propeller never moves as far forward as the pitch would suggest since the water slips around the propeller as it is spinning. The difference between how far the propeller should move in the water and how far that it actually moves is known as apparent slip. In order to accommodate for the presence of slip, the pitch must be made larger by multiplying it by an empirically determined correction factor.

Figure 8. Hubless propeller designed and manufactured for PropaGator 2

After the pitch had been determined, the diameter of the propeller was calculated. Ideally, since the goal is to reduce the drag caused by the propeller assembly, it would be best to make the propeller as small as possible. While a very small propeller could provide adequate thrust at high speeds, it may not be able to provide enough thrust at lower speeds to reach the planing state or to effectively maneuver. To determine the minimum diameter the following equation was used,

$$D_{min} = 4.07 \cdot \sqrt{BWL \cdot H_d}, \quad (6)$$

where D_{min} is the minimum required diameter to provide useful thrust at all speeds measured in in, BWL is the beam on the waterline measured in ft, and H_d is the draft of the hull measured in ft. Since PropaGator 2 is designed to be a twin-screw vessel, D_{min} must also be made smaller by being multiplied by an empirically determined correction factor.

Typically propellers with two blades are more efficient than propellers with more blades. However, in order to get the blade area required for effective thrust, they require a large diameter. Since the goal was to minimize the diameter of the propeller as much as possible, a three-bladed propeller was designed. The extra blade allows for additional blade area without increasing the propeller's overall diameter. Other common propeller parameters are rake and skew, but after researching how they affect the performance of the propeller, it was decided that their inclusion in the propeller design did not offer any advantage to the application of PropaGator 2.

Once all of the propeller parameters were determined, shown in Table I, a CAD model of the propeller was generated and then machined on a 4-axis CNC mill. In order to provide resistance to moisture, long-term fatigue endurance, and high strength and rigidity, the propellers were cut out of blocks of Delrin.

Table I. Propeller Parameters

Parameter	Value
Number of blades	3
Diameter	3.5 in
Pitch	7 in
Rake	0°
Skew	0°
Cross section shape	NACA 66-006
Developed blade area	1.2 in^2

6. RESULTS

The maximum velocity of PropaGator 2 is 11 kts and was recorded by using the velocity log from a Yuan 10 Skytraq S1315F-RAW GPS. The final displacement for the ASV was 95 lbf. It can fit within a box with the dimensions of 72 in x 35 in x 21 in and has a maximum payload of 200 lbf. Since the hull's mold has already been fabricated, to build an exact replica of PropaGator 2 would cost less than $15,000.

In July of 2014, PropaGator 2 competed against other ASVs from around the world at AUVSI Foundation's 7th Annual RoboBoat Competition. In addition to winning the Innovation Award for Hull Form and Propulsion Design, it outperformed all of the other ASVs in the propulsion based metric. PropaGator 2 produced a maximum of 56 lbf of thrust in a static thrust test where the ASV pulled on a scale that was tethered to the dock. The next strongest ASV was only able to produce 17 lbf of thrust.

7. CONCLUSION

In this paper, the research and testing that went into the mechanical design and implementation of PropaGator 2 has been described. A description of the design and shortcomings of PropaGator 1 lead to the motivation for developing an ASV capable of travelling 10 kts. The hydrofoil research and drag testing motivated the planing hull design used for PropaGator 2. The design of the various components of the steering and propulsion system was then detailed. The performance of the ASV was measured and was found to have exceeded all of the original design criteria.

Future development goals include redesigned motor pods with a motor built directly around the propeller inside of the Kort nozzle shroud. Some of the advantages of this new thruster are that it will allow the water to act as a natural heat sink for the motors and it will eliminate the chance for a timing belt to loosen or break. The new thruster will also feature fewer and easier to access parts, which will require less maintenance than the current thrusters. Additionally, further empirical testing will be performed to improve the design of the propellers for the ASV. Finally, the ASV will be outfitted with radio frequency (RF) transmitters and receivers so that it can coordinate missions with other ASVs or an unmanned aerial vehicle (UAV).

8. ACKNOWLEDGEMENTS

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REFERENCES

[1] Gray, A., Shahrestani, N., Frank, D., and Schwartz, E., 2013, "PropaGator 2013: UF Autonomous Surface Vehicle," AUVSI Foundation's 6th Annual RoboBoat Competition, Virginia Beach, VA.

[2] Weaver, J., Frank, D., Schwartz, E., and Arroyo, A., 2013, "UAV Performing Autonomous Landing on USV Utilizing the Robot Operating System," Proc. ASME District F - Early Career Technical Conference, Birmingham, AL, pp. 119–124.

[3] Savitsky, D., 1985, "Planing Craft," Naval Engineers Journal, 97(2), pp. 113–141.

[4] Eppler, R., 1990, Airfoil Design and Data. Springer-Verlag, Berlin, DE, Chap. 6.

[5] Cengel, Y., and Cimbala, J., 2010, Fluid Mechanics : Fundamentals and Applications 2nd ed., McGraw-Hill Higher Education, New York, NY, Chap. 7.

[6] Lamb, T., 2004, Ship Design and Construction Vol. II, Society of Naval Architects and Marine Engineers, Chap. 45.

[7] Savitsky, D., 1964, "Hydrodynamic Design of Planing Hulls," Marine Technology, 1(1), pp. 71–95.

[8] Patel, D., Frank, D., and Crane, C., 2014 "Controlling an Overactuated Vehicle with Application to an Autonomous Surface Vehicle Utilizing Azimuth Thrusters," Proc. 14th International Conference on Control, Automation, and Systems, Gyeonggi-do, KR, accepted.

[9] Hsieh, M.-F., Chen, J.-H., Yeh, Y.-H., Lee, C.-L., Chen, P.-H., Hsu, Y.-C., and Chen, Y.-H., 2007, "Integrated Design and Realization of a Hubless Rim-Driven Thruster," Proc. IECON 2007, 33rd Annual Conference of IEEE Industrial Electronics, Taipei, Taiwan, pp. 3033–3038.

[10] Carlton, J., 2007, Marine Propellers and Propulsion 2nd ed., Butterworth-Heinemann, Oxford, UK, Chap. 2.

[11] Yakovlev, A. Y., Sokolov, M. A., and Marinich, N. V., 2011, "Numerical Design and Experimental Verification of a Rim-Driven Thruster," Proc. 2nd International Symposium on Marine Propulsors, Hamburg, DE, pp. 396–402.

[12] Cao, Q.-M., Hong, F.-W., Tang, D.-H., Hu, F.-L., and Lu, L.-Z., 2012, "Prediction of Loading Distribution and Hydrodynamic Measurements for Propeller Blades in a Rim Driven Thruster," Journal of Hydrodynamics, 24(1), pp. 50 – 57.

[13] Gerr, D., 1989, Propeller Handbook, International Marine, Camden, ME, Chap. 5.