Design of the Life-ring Drone Delivery System for Rip Current Rescue

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***Abstract* - Over 40% of the United States population visit the beach each year. For the 10 year period between 2003 and 2012, lifeguards made on average 67,700 rescues per year. Rip currents account for 80% of annual beach rescues and fatalities. When a lifeguard spots the victim, the lifeguards must reach the victim before a mean time of 102 seconds (σ = 30s). This paper presents the design of the Life-ring Delivery Drone System, which delivers life-rings to victims faster than a lifeguard. Once victims have a life-ring, they can survive long enough until the lifeguard reaches them. A stochastic simulation of rip-current victim's location and time-to-drown was used to determine the optimal drone launch location of near a lifeguard tower, and operational range covering one lifeguard section while using a flight path avoiding overhead flight of beach goers. An Analytical Hierarchy Process determined that a tethered life ring is the best flotation device for this application. The drone size-weight-power design space was analyzed with a system dynamics model to determine that an octocopter with a 1000 mm wheelbase, 10.2 kg total weight, using a battery with 20000 mAh energy capacity provide the optimal size, power, and endurance. The weight capacity of the drone and the maximum battery power output are the main attributes that limit the drone's performance. Stronger motors, lighter battery, and higher power rating can lead to a faster drone. The Life-ring Delivery Drone System results in a reduction in mean time to reach a victim of 39% (reducing standard deviation by 66%), reducing the probability of a failed rescue from 92.3% to 99.4%.**

Index Terms - Lifeguard Beach Rescue Process, System Dynamics Model, Unmanned Aerial Vehicle, Utility-Cost Model.

Introduction

I Beach Analysis

96 million Americans visited an ocean front beach in 2007, 10.5% more people than in 2000 [1]. The EPA states there are 6,258 beaches in the United States [2], and their combined annual revenue is more $320 billion dollars per year [3]. On any sizable beach, there are lifeguards that make sure beach goers are safe.

II Beach Incidents

Looking at statistical data from the United States Life Saving Association (USLA) between 2003 and 2014, and the National Oceanic and Atmospheric Administration (NOAA), rip currents cause the vast majority of both rescues and fatalities. Rip currents accounted for 67,700, or nearly 80%, of annual rescues [4][5]. Additionally, rip current drowning accounts for 79% of all beach fatalities [6]. NOAA reports the 10-year average of annual rip current fatalities as 51 in the United States [7]. However, USLA reported the average annual fatalities as exceeding 100 people [8].

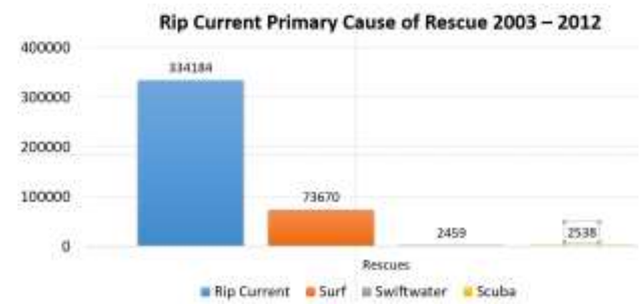

FIGURE I
RIP CURRENTS ARE ABOUT 80% OF RESCUES ACCORDING TO USLA [5].

III Rip Currents

Rip currents are powerful currents of water that flow away from shore. Rip currents form when waves break near the shoreline and generate feeder currents that move along shore [9]. Rip currents occur at every beach. There are typically multiple rip currents spread across the shoreline. Ephemeral rip currents have a duration lasting from a few hours to a few days. Persistent rip currents can last for many days in one location.

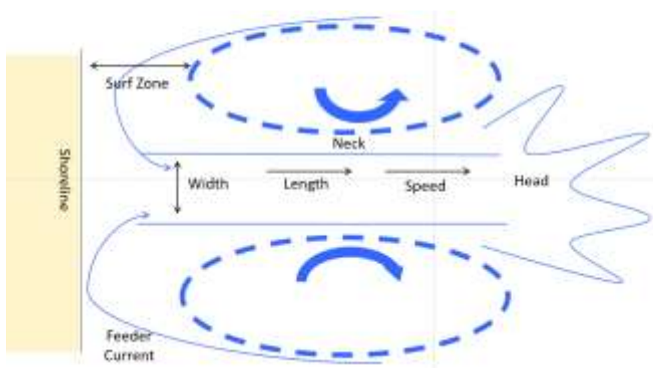

FIGURE II
RIP CURRENTS HAVE BOTH A NECK AND A HEAD. THE NECK IS WHERE THE RIP CURRENT'S SPEED AND STRENGTH IS HIGHEST. ITS WIDTH RANGES BETWEEN TEN AND TWO HUNDRED FEET. ITS LENGTH CAN BE HUNDREDS OF

FEET. THE SPEED OF THE RIP CURRENT RANGES FROM ONE TO EIGHT FEET PER SECOND [10][11].

The best method for escaping a rip current is to swim parallel to the shoreline thus escaping the neck first, then swimming back to shore. However, some victims do panic and either float or fight against the current [11].

IV Lifeguard Rescue Process

The beach is separated into multiple sections of a few hundred meters with one lifeguard tower centered in each zone. If a drowning victim is spotted in the zone, the lifeguard will radio the control room, whistle at the adjacent lifeguards to cover their zone, and then point in the direction of the victim [12]. The lifeguard runs along shore to the rip current, swims to the victim, rescues them, guides them back to the shoreline, and then drags them out of the water. Medical care is provided as needed afterwards. The entire lifeguard rescue process takes a max of 4 minutes [13][14].

V Performance Gap

There is a gap between victim survival time and lifeguard rescue time; lifeguards can reach a victim in a maximum of 93 seconds, however some victims can have survival times as low as 60 seconds [13]. This gap in survival time and rescue time causes fatalities to occur.

VI Stakeholder Analysis

There are five main stakeholders: 1) lifeguarding associations, 2) lifeguards, 3) beach goers, 4) manufacturers, and 5) municipalities. Lifeguarding associations train and certify beach lifeguards. Lifeguards supervise the safety and rescue of beachgoers. Beach goers are people who go to the beach and use its services. Manufacturers produce equipment for the lifeguards. Lifeguarding associations can also manufacture their own rescue products. Municipalities are broken down into owner and operator. The owner can be the county, city, or state government that owns the beach property. The operator documents the lifeguards current status of certification and requirements met.

VII Stakeholder Tensions

Rip currents continue to be a problem because beach goers usually do not follow advice from lifeguards, and rip currents are difficult for beach goers to spot. The beach owner is always liable for the beach goers if they are injured during the lifeguard rescue process. The beach owner is protected under the catastrophic umbrella insurance for any huge damage. The beach goers provide the revenue for the beach operator and businesses [12].

PROBLEM STATEMENT

I Problem Statement

On average, rip currents are the cause of 81% of annual beach rescues, 79% of annual beach fatalities, and cause a minimum of 51 deaths per year [5][6][7]. Lifeguards can reach a victim caught in a rip current in a max of 93 seconds [13][14]. However some victims cannot survive this long, as some have survival times as low as 60 seconds.

II Proposed Design Solution

To increase victim survival time during the rip current rescue process, a system was designed to deliver a flotation device to the victim. Once a victim has the flotation device, they will be able to survive long enough for lifeguard rescue. The flotation device will be derived by an unmanned aerial drone.

CONCEPT OF OPERATIONS

The two main requirements are: 1) the system must deliver a flotation device that weighs at most 2.268kg within the grasp of the victim and this must be done faster than the lifeguard; and, 2) the system must at least be usable in the United States so it must be designed to meet FAA regulations regarding the use of drones.

A multi-rotor drone will facilitate the delivery of a flotation device that can be tethered to and released from the drone. The drone rescue process proceeds as follows:

1. Lifeguard radios in an occurring rescue in a section.
2. Pilot hears call on radio.
3. Pilot commands drone to lift off and fly to the section.
4. Drone verifies victim position by on-board cameras.
5. Drone flies to victim, descending on the way.
6. Drone releases tether to lower the flotation device, but still hold the tether to manipulate its position in the water.
7. Drone pulls flotation device to victim then releases the tether when the victim grabs the flotation device.
8. Once victim has secured flotation device, drone flies back to home point.

FIGURE III

A MODEL OF THE LDDS DRONE MADE IN AUTODESK INVENTOR. FIRST IMAGE IS THE HOLD STAGE, WHERE THE DRONE IS ABLE TO MANIPULATE THE FLOTATION DEVICE IN THE WATER. ONCE THE VICTIM GRABS HOLD OF THE FLOTATION DEVICE, THE DRONE RELEASES THE TETHER, SHOWN IN THE SECOND IMAGE. THE THIRD IMAGE, THE DRONE CARRIES THE FLOTATION DEVICE UNTIL IT LOCATES THE VICTIM.

DESIGN ALTERNATIVES

I Flotation Device

The following four flotation devices were considered: life rings, life vests, rescue cans, and an inflatable life jacket called the Ultra 3000.

II Optimal Battery Properties

A complex design space limits the drone's weight and battery capacity. The more weight the drone carries, the more thrust it needs; the more thrust it needs, the more power it needs; the more power it needs, a bigger battery is needed, which is also heavier. Thus a battery that provides enough power while remaining relatively light is necessary. Another criterion is the battery must have at least a 10,000 mAh energy capacity.

III Drone Home Point Location

The locations considered are at the lifeguard tower or on a boat. The operational range of the drone shall be defined as the number of sections on the beach that the drone will be responsible for covering. Two ranges are considered: 1 section (drone only responds to the closest tower) and 3 sections (responds to closest section and one section to the left and right.)

IV Drone Flight Path

With the need for the drone to be operable anywhere in the US, the authors must consider how to avoid overhead flight. Thus, a flight going around the area close to the shore is considered. The situation where the FAA can loosen this restriction is also considered, where the drone will fly directly to the victim, with little care for other beachgoers.

METHOD OF ANALYSIS

A simulation was developed in order to verify that the LDDS system does in fact decrease time-to-reach-victim, increase the probability of victim survival, and to determine the best design choices to allow the system to perform best in a rip current rescue. Equations for frames of references, power output, linear motion, and rotation were used in order to simulate the addition of a drone into the rescue process [15] [16].

I Frames of Reference

Drones have an even number of motors (four, six, or eight). Half the motors spin counterclockwise and the other half spin clockwise. By having motors that spin in different ways, the drone can control rotation about its axes.

There are two important frames of reference considered. The drone's reference points (body-frame) and the controller's reference point (inertia-frame). In order to convert rotation between the body-frame and inertia-frame, the following translational matrices will be used.

$$R_\psi = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$R_\theta = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \quad (2)$$

$$R_\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \quad (3)$$

$$R = R_\psi R_\theta R_\phi = \begin{bmatrix} \cos\theta\cos\psi & \sin\psi\cos\phi+\sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi-\cos\phi\sin\theta\cos\psi \\ -\cos\theta\sin\psi & \cos\phi\cos\psi-\sin\phi\sin\theta\sin\psi & \sin\phi\sin\psi+\cos\phi\sin\theta\cos\psi \\ \sin\theta & -\sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \quad (4)$$

Additonally, another transformation matrix will be used to convert angular acceleration to derivatives of roll-pitch-yaw.

$$\begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \sin\phi\cos\theta \\ 0 & -\sin\phi & \cos\phi\cos\theta \end{bmatrix} \begin{bmatrix} \dot\phi \\ \dot\theta \\ \dot\psi \end{bmatrix} \quad (5)$$

II Power Equations

To determine power, we used the following three equations.

$$\tau = K_t(I - I_0) \quad (1)$$

$$V = IR_m + K_v\omega \quad (7)$$

$$\tau = K_\tau T \quad (8)$$

Where τ is motor torque, I is current, I_0 is the no-load current, K_t, K_v, K_τ are proportionality constants, V is voltage, ω is the angular velocity of the motor's propeller, and T is the propeller's thrust. From (6) (7) and (8), power is calculated using voltage and current.

III Linear Motion

The thrust equation used is given below:

$$T = \sqrt[3]{(\pi/2)D^2\rho P^2} \quad (2)$$

Where T is a motor's thrust, D is diameter of the propeller, ρ is the air density, and P is power. Substituting power from (6) (7) (8) gives the thrust force vector in terms of motor angular velocity.

IV Drag Model

The following equation was used to calculate force of drag:

$$F_D = (1/2)(C_D\rho v^2 A) \quad (3)$$

Where F_D is force vector due to drag, C_D is the coefficient of drag of the drone, ρ is the air density, v is the velocity of the drone, and A is surface areas normal to the X-Y-Z axes.

A model of the LDDS system was made in Autodesk Inventor to determine the drag coefficients. The drag coefficients are for the drone moving in 55 mph, laminar flow winds. C_D for the hexacopter's X-Y-Z axis are respectively, 0.9, 0.9, and 1.1 respectively. Octocopters have X-Y-Z drag coefficients as 0.9, 0.9, and 1.2 respectively. Surface area was approximated by assuming the arms were cylinders, and the base was an octagonal or hexagonal prism.

V Main Force Model

With equations for the force of thrust (10), force of drag

(11), and force due to the life ring (13), net force can be calculated as well as mass multiplied by acceleration. Double integration of acceleration gives the position of the drone in the inertia-frame.)

$$m\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{bmatrix} = \begin{bmatrix}0\\ 0\\ -mg\end{bmatrix} + RT_{body} + F_D + F_{LR} \qquad (4)$$

Where m is the mass of the drone system, a is the acceleration, x, y, z are the 3-dimensional inertia-frame position values of the drone, g is acceleration due to gravity, R is the rotational matrix to convert body-frame forces to inertia-frame force (4), and F_{LR} is the force due to the life ring which is decomposed into the life ring's weight force and drag force.

VI Rotational Dynamics Model

The torques for roll, pitch, and yaw were developed below. For yaw torque, (16) was used per motor to add up their yaw torques (counterclockwise is positive). The below equation is for octocopters.

$$\tau_B = \begin{bmatrix}\tau_\varphi\\ \tau_\theta\\ \tau_\psi\end{bmatrix} = \begin{bmatrix} Lk(\omega_1^2 + \omega_2^2 - \omega_5^2 - \omega_6^2)\\ Lk(\omega_3^2 + \omega_4^2 - \omega_7^2 - \omega_8^2)\\ \tau_D(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2 + \omega_5^2 - \omega_3^2 + \omega_6^2 - \omega_7^2 + \omega_8^2)\end{bmatrix} \qquad (12)$$

Where τ_φ, τ_θ, and τ_ψ are the torques for roll, pitch, and yaw, L is the distance from a motor to the center of mass, τ_D is the torque on the propellers due to drag, and k is the coefficient for total thrust and the sum of motor angular velocities.

To get roll, pitch, and yaw values, the follow equation is used.

$$\tau = I\dot{\omega} + \omega \times (I\omega) \qquad (5)$$

Once angular acceleration is derived, equation (5) is used to calculate derivatives of φ-θ-ψ. Integrating those will get roll, pitch, and yaw angle values.

VII Simulation

In order to determine if the LDDS improves rescue and decrease fatalities, a system dynamics model was developed using MATLAB. The system dynamics model simulates a rip current rescue involving victims acting escape methods in a rip current, and lifeguards attempting to reach the victim. The LDDS is introduced into the rescue process and the results are analyzed. This model assumes no waves, no other swimmers, and victims only attempting one escape method.

For the entirely of the simulation. Inputs are: chosen escape methods, rip current speed, distance from tower, width, and length. State variables are victim position, lifeguard position, and drone position over time. As shone if figure IV, the final block analyzes positions to determine the time needed to reach the victim and whether the victim survives.

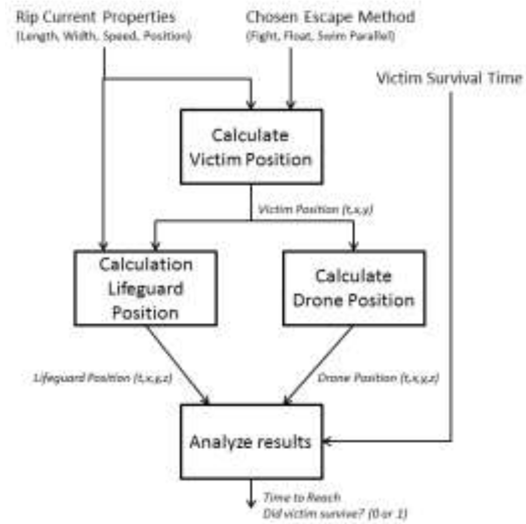

FIGURE IV

SIMULATION BLOCK DIAGRAM.

VIII Rip Current & Victim Behavior

The position of the victim is calculated over time. Assume victim velocity is constant. The distributions below were gathered from interviews with lifeguards [13].

TABLE I

DISTRIBUTION OF RIP CURRENT PROPERTIES AND VICTIM ESCAPE BEHAVIOR

Properties	Distribution
Rip Current Length	Unif(30.48 – 91.5 m)
Rip Current Speed	Unif(0.308 - 2.438 m/s)
Rip Current Width	Unif(3.048 - 60.96 m)
Victim Escape Method (0,1,2)	{0.4, 0.25, 0.35}
Victim Swim Speed (not float)	Norm(1.161 m/s, 0.267)
Float Survival	Norm(80 sec, 20)
Fight Current Survival	Norm(130 sec, 20)
Swimming Parallel Survival	Norm(180 sec, 20)

The victim survival distributions were estimated from Frank Pia, who did video analysis on over 40,000 rescues in a 20-year period [17] [18]. Non-swimmers can last on the surface for 20 to 60 seconds. Rip current victims usually are still able to swim for some time before tiring. Thus, assume an additional 20-60 seconds for swimming. Assuming this range represents 95% of swimmers, a normal distribution is approximated, to fit Captain Arben's estimates [13].

IX Drone Dynamics and Control

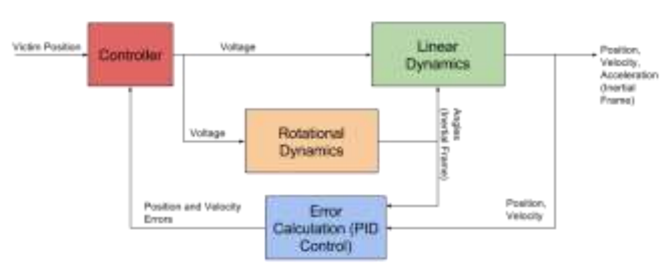

FIGURE V

MAIN MODEL OF DRONE MOVEMENT AND ROTATION

The drone position was calculated over time. Figure 5 shows the drone dynamics. The victim's position comes to the controller, which outputs a voltage to linear and rotational dynamics. These output drone velocity, position, and Euler angles. These go to a PID error calculation to get the error in wanted velocity and position. These errors go back to the controller, which adjusts the voltage.

RESULTS

I Flotation Device

To determine the best flotation device to be delivered, an AHP analysis was done based on attributes of effectiveness, usability, buoyancy, dimensions, and weight/mass. Results show that the life ring is the best choice.

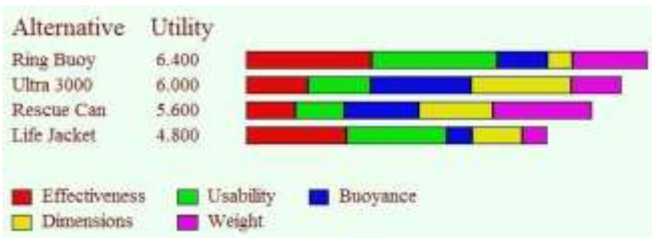

FIGURE VI

AHP RESULTS FOR THE FLOTATION DEVICE ALTERNATIVES. WEIGHTS FOR EACH ATTRIBUTE WERE DETERMINED THROUGH LIFEGUARD INTERVIEWS WITH THE AUTHORS [13].

II Battery Selection

Power draw for the drones were calculated from the simulation as the drones performed and maintained three maneuvers - hover, constant speed level flight, and accelerating level flight. Total power output is calculated at steady state, assuming the drone will be at steady state at 3 minutes. Results are shown in Figure 11. The two best batteries and their properties are shown in Table 2.

FIGURE VII:

BLUE DOTS REPRESENT THE POWER NEEDED TO ACCELERATE AT 1 M/S. BATTERIES THAT FALL BELOW THIS LINE DO NOT PROVIDE ENOUGH POWER. ORANGE DOTS REPRESENT REAL WORLD BATTER POWER. THE VERTICAL BLACK LINE DENOTES THE MAXIMUM RECOMMENDED WEIGHT OF THE DRONE - ANY MORE WEIGHT AND PERFORMANCE CANNOT BE GUARANTEED.

TABLE II

THE BEST RESULTING BATTERY PROPERTIES

Chosen Batteries for:	Battery Name	Cost	Energy Output (>10000mAh)	Mass (kg)
Hexacopter	Tattu 12000	248.00	12000mAh	1.62
Octocopter	Power 20000	347.74	20000mAh	2.492

III Case Study

A case study is conducted to determine if a certain beach benefits from using the LDDS. The chosen beach is Galveston Island Beach, Texas based on the USLA 2014 record where 65 rip current rescues were attempted there with 3 rip current deaths that year [4]. Assume all deaths involved attempted rescues. This beach has a 400 yard average distance between towers and 6 miles of covered beach area (estimated 25 towers).

IV Location and Path

Drones with different location-path combinations flew to victims, assuming constant speed. The results of the experiment are shown below. The minimum velocity is defined as the velocity needed reach at least 80% of the victims within 60 seconds. A high minimum velocity means the drone has a smaller time window to reach the victim. Results are shown on Figure 12. The best locations for Galveston are at tower, covering 1-section or 3-section. Path did not affect results.

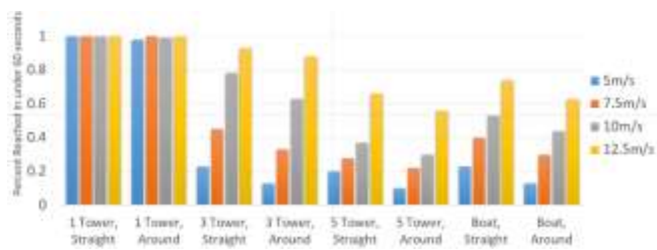

FIGURE VIII

COMPARISON OF LOCATION-PATH COMBINATIONS WITH % REACHED UNDER 60 SECONDS. THE Y-AXIS IS % REACHED UNDER 60 SECONDS. THE BOAT COVERS 5 SECTIONS.

V Evaluating Rescue Alternatives

The final experiment determines how the hexacopter and octocopter rescues compete with lifeguard rescue. The drones were modelled after DJI's S900 and S1000+ specifications [21]. The simulation ran for 325 victims. Results shown below:

TABLE III

MEAN TIME TO REACH VICTIM, STANDARD DEVIATION, AND PERCENT OF VICTIMS SAVED FOR EACH ALTERNATIVE

Time to Reach	Mean (s)	Standard Deviation	% Saved
Lifeguard	50.41	31.50	92.3
Hexacopter 3-S	62.62	22.02	88.3
Octocopter 3-S	59.07	20.55	90.8
Hexacopter 1-S	32.19	13.01	99.4
Octocopter 1-S	30.78	10.85	99.4

The octocopter has a faster time to reach and a smaller standard deviation compared to the hexacopter while being nearly the same cost, thus the octocopter is the best choice as the drone platform to use. An operational range of three sections has a lower percent saved compared with the baseline lifeguards, thus one section is the best operational range.

Based on lifeguard-only rescue, the LDDS octocopter reduces the mean time to reach by 39%, and reduces the standard deviation by 66%, cutting the probability of a failed rescue by a factor of 13.

VI Cost Model

Drone costs were gathered from interviews with a representative from ExpertDrones [19]. The acquisition and annual costs of the LDDS are shown below.

TABLE IV
ACQUISITION AND ANNUAL COSTS OF THE LDDS SYSTEM

Acquisition Costs	Cost
Drone Platform (s1000+)	$2,670
Two Cameras	$399.99
Battery (8 batteries)	$2781.92
Battery Charger	$126
Location Setup	$500
User Training (8hr)	$2,392
Total	$8,869.91
Annual Operation & Support	Cost
Annual Repair Cost	$500
Annual Battery Recharging	$51.24
Tether 25ft	$42
Total	$593.24

VII Cost of Life

The cost of life considered is the payout due to the victims' families suing the lifeguards. Analyzing seven settlements against lifeguards for negligence, the settlement amount averages $120,000. For our utility analysis, assume a 25% probability of litigation for every person that fails to be rescued.

VIII Cost vs % Saved

Since there are 25 towers, the cost is multiplied by the number of LDDS systems built. Thus the 5-year cost in current dollars is shown below:

TABLE V
5 YEAR COST AND 5 YEAR COST WITH FLIGHT SCHOOL COSTS SET AT $5000

Alternatives	5-year cost per drone	Total 5-year Cost	% Saved
Lifeguard Only		$797,605.60	92.3
Octocopter 1-S	$183,718.41	$4,592,960.25	99.4
Flight school at $5000			
Octocopter 1-S	$16,827.23	$480,680.75	99.4

Shown above, the cost of the LDDS is much higher than the cost of lifeguard rescue due to the high salary of licensed pilots. The reason a licensed pilot is required is because the controller needs to able to read aeronautical charts. Thus, another case is that the FAA allows lifeguards to go through flight school, and take a test to show competency. With the assumption of loosened restrictions, the LDDS increases the chance of successful rescue while also lowering total costs due to lowering the number of possible settlements.

RECOMMENDATIONS

To maximize the success rate of the rip current recue, the authors determined that the most successful LDDS configuration has the highest number of successful rescues with the following configuration: an octocopter with a 1000 mm wheelbase, 10.2 kg total weight, using a battery with 20000 mAh energy capacity, equipped with a tethered life ring, launched from a location near a lifeguard tower, covering one lifeguard section, using a flight path avoiding overhead flight.

To use an example, the authors consider a case of Galveston Texas, the best option is to keep their baseline of lifeguards due to the high cost of the LDDS pilot. If the FAA loosens this restriction and allows student pilots, then the best choice is 25 LDDS drones that cover 1 section each.

ACKNOWLEDGMENT

Brett Velicovich, Brian Yi, Captain Butch Arben III, lifeguards at Ocean City and Miami Beach, Dane Underwood, and Dr. Lance Sherry

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